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RESEARCH AND DEVELOPMENT
(R&D) 2**

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Fuel Properties - 2004 Third Edition**

**Coordinating Research Council, Inc.
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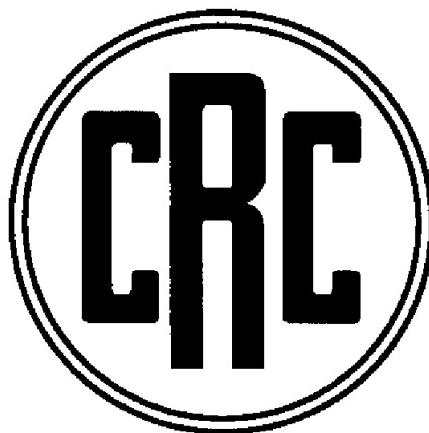
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14. ABSTRACT Aviation and air breathing missile fuels are characterized and controlled by specifications and by contract. Specifications for aviation fuels have historically been based primarily on usage requirements as opposed to detailed chemistry. Exceptions would be chemically derived, military fuels such as JP-10, as well as certain other missile fuels. Over the years aviation gasoline (Avgas) has become composed primarily of synthetic components, while turbine fuels are largely straight-run distillates and therefore depend on crude oil type for their primary characteristics. Synthetically derived hydrocarbons in the kerosene boiling range generally have properties that fall within the specification range for aviation turbine fuels. However, these fuels must meet rigorous engine and compatibility tests before they are accepted for use.						
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HANDBOOK OF AVIATION FUEL PROPERTIES

2004 Third Edition



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HANDBOOK OF AVIATION FUEL PROPERTIES

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2004 Third Edition

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FOREWORD

The purpose of this document is to provide a convenient source of information on properties of aviation fuels for reference use. The data presented herein have been compiled by the CRC Aviation Handbook Advisory Group from the latest known sources on each particular subject. Where conflicts arose owing to discrepancies in source material, they have been resolved by decision of the Group. The references cited document the source of information including references no longer in print.

This document was made possible by the contributions of industry and government personnel considered experts in their respective fields. Tedd Biddle of Pratt & Whitney served as Leader of the Coordinating Research Council (CRC) Advisory Group responsible for updating this handbook. Stan Seto of General Electric Aircraft Engines served as Co-leader. Kurt Strauss, Consultant, served as editor. Bill Taylor of W. F. Taylor Associates prepared Section 2, "Fuel Properties" under contract to CRC. Melanie Thom of Baere Aerospace Consulting wrote the initial draft of Section 1, "Description of Fuels" and Section 3, "Fuels and Distribution System Issues" under contract to W.F. Taylor Associates. Christopher Bunker of the Air Force Research Laboratory at Wright-Patterson Air Force Base performed the spectroscopy that makes up Section 4, "Spectral Characterization." Tim Edwards of the Air Force Research Laboratory at Wright-Patterson Air Force Base contributed to the source data and understanding of thermal conductivity of jet fuels. Teresa Hocevar of Pratt & Whitney was responsible for putting the text and graphics of the document in publishable form. The draft review team was comprised of the following experts:

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ACRONYMS

A

AFQRJOS	Aviation Fuel Quality Requirements for Jointly Operated Systems
AIT	Autoignition Temperature
ALCM	Air Launched Cruise Missile ,
API	American Petroleum Institute
APU	Auxiliary Power Unit
ASALM	Advanced Strategic Air-Launched Missile
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
Autogas	Unleaded Automotive Gasoline
AVCAT	High Flash Kerosene (NATO F-44)
Avgas	Aviation Gasoline
AVTAG	Aviation Turbine Fuel - Wide-Cut
AVTUR	Aviation Turbine Fuel

B

BOAC	British Overseas Airways Corporation
BOCLE	Ball-on-Cylinder Lubricity Evaluator
BTU	British Thermal Unit

C

CGSB	Canadian Government Standards Board
CRC	Coordinating Research Council, Inc.

D

Def Stan	Defence Standard (British)
DERD	Directorate of Engines, Research and Development
DESC	U.S. Defense Energy Support Center
DiEGME	Diethylene Glycol Monomethyl Ether
DoD	U.S. Department of Defense (U.S.)

E

EGME	Ethylene Glycol Monomethyl Ether
EPA	Environmental Protection Agency (U.S.)

F

Fluid I	Ethyl Cellusolve
Fluid I-M	Ethyl Cellusolve and Methanol
FSII	Fuel System Icing Inhibitor
FTHWG	Fuel Tank Harmonization Working Group

G

GB	Chinese National Standard
GM	Guidance Material
GOST	Russian National Standard

H

HSIT	Hot Surface Ignition Test
Hz	Cycles per second

I

IATA	International Air Transport Association
IATA	International Aviation Transport Association
IMEP	Indicated Mean Effective Pressure
IP	Institute of Petroleum (British)
IR	Infrared Absorption
IRS	Internal Revenue Service

J

JCL	Joint Check List
JFA-5	Jet Fuel Additive No. 5
JFSCL	Joint Fuelling Systems Check List
JFTOT	Jet Fuel Thermal Oxidation Tester
JP-TS	Jet Propulsion Thermally Stable

K

kJ/kg K	Kilo Joules per Kilogram Kelvin
---------	---------------------------------

L

LL	Low Lead (Avgas)
LRCSW	Long Range Conventional Standoff Weapon

M

MDA	Metal Deactivator Additive
MJ/kg	Mega Joules Per Kilogram
MJ/m ³	Mega Joules Per Cubic Meter
MOD	Ministry of Defence (British)
Mogas/Autogas	Motor Gasoline - Unleaded
MSDS	Material Safety and Data Sheets
MSEP	Microseparometer
mW	Milliwatts

N

NATO	North Atlantic Treaty Organization
NIPER	National Institute of Petroleum and Energy Research (formerly Bureau of Mines)
NIR	Near Infrared
nm	Nanometer

O

OEM	Original Equipment Manufacturer
-----	---------------------------------

P

P&W	Pratt & Whitney
ppm	Parts Per Million
pS/m	picoSiemens/meter

Q

QPL	Qualified Products List
-----	-------------------------

S

SDA	Static Dissipator Additive
STC	Supplemental Type Certificate
STM	Standard Test Method

T

TD	Tube Deposit Rating
TEL	Tetraethyl Lead

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TGF	Tetrahydrafurfuryl Alcohol
TGF-M	Tetrahydrafurfuryl Alcohol and Methanol
TS	Thermal Stability

U

UL	Unleaded, aviation or automotive gasoline
----	---

W

W	Watt
W/m K	Watt Per Meter Kelvin
WSD	Wear Scar Diameter
WW I	World War I

1. DESCRIPTION OF FUELS

1.1 FUEL SPECIFICATIONS

Aviation and air breathing missile fuels are characterized and controlled by specifications and by contract. Specifications for aviation fuels have historically been based primarily on usage requirements as opposed to detailed chemistry. Exceptions would be chemically derived, military fuels such as JP-10, as well as certain other missile fuels. Over the years aviation gasoline (Avgas) has become composed primarily of synthetic components, while turbine fuels are largely straight-run distillates and therefore depend on crude oil type for their primary characteristics. Synthetically derived hydrocarbons in the kerosine boiling range generally have properties that fall within the specification range for aviation turbine fuels. However, these fuels must meet rigorous engine and compatibility tests before they are accepted for use.

Over the years aviation gasolines have improved drastically, particularly in their resistance to knock. Turbine fuels, on the other hand, have had a different history. Originally it was thought that a jet engine would operate on nearly any fuel source. Now turbine fuels have the most extensive specifications of all fuels, a trend driven by the performance requirements identified over the years. Yet the overall composition has changed relatively little over that time. Aviation turbine fuels are required to be solely hydrocarbon compounds with select approved additives except where otherwise specified. However, certain hydrocarbon types such as aromatics are limited by fuel and engine system performance requirements. These system demands are the primary determinants of the specification requirements, including such properties as fluidity, stability, as well as physical properties affecting atomization and combustion. Specifications also control additives by type and concentration. In aviation gasolines these include anti-knock compounds, dyes, oxidation inhibitors and anti-icing compounds. In turbine fuels the additives affect performance properties of the fuel such as thermal stability, oxidation resistance, lubricity, electrical conductivity, and icing characteristics. Other additives are used to detect fuel leaks or to control microbial growths. Missile fuels are controlled by specific chemical composition. Here the chemical composition has been tailored to satisfy the unique demands of the vehicle. Additives used are also specified to help meet the exacting requirements of the application.

1.1.1 Aviation Gasoline

United States Civil Aviation Gasoline

Current civil aviation gasoline specifications cover Grades 80, 91, 100, 100 low lead (LL), and 82 UL fuels. Specification details for the leaded grades are shown in **Table 1-1** and are based on ASTM D 910. (The following specification tables are for general information only and readers should refer directly to applicable documents for specific information. The reader should note that specifications often contain requirements not listed in the table. Sources for the various specifications are given at the end of this section.) The grades 100 and 100LL meet the same requirements except for lead content and color. Depending on specific engine models, the 100LL grade may be suitable for engines with an 80 octane requirement as well as engines with an 100 octane requirement. There is no civil aircraft demand for the ultra-high octane grade, 115/145, listed in older versions of the specification. The 91 grade has been added recently for engines certified on this grade.

Table 1-I. U.S. Commercial Aviation Gasoline Specifications – Grades 80, 91, 100LL, and 100

Property	Requirement				ASTM Test Method
	Grade 80	Grade 91	Grade 100LL	Grade 100	
COMBUSTION					
Knock Value, Lean Mixture, Motor Method					D 2700
Octane Number	Min	80.0	91.0	99.5	99.5
Knock Value, Rich Mixture, Supercharge Rating					D 909
Octane Number	Min	87.0	98.0	130.0	130.0
Performance Number ^{1, 2}	Min				
Tetraethyl Lead, mL TEL/L g Pb/L	Max	0.13	0.53	0.53	1.06
	Max	0.14	0.56	0.56	1.12
COLOR					
Color		Red	Brown	Blue	Green
Dye Content ³					D 2392
Blue Dye, ⁴ mg/L	Max	0.2	3.1	2.7	2.7
Yellow Dye, ⁵ mg/L	Max	None	None	None	2.8
Red Dye, ⁶ mg/L	Max	2.3	2.7	None	None
Orange Dye, ⁷ mg/L	Max	None	6.0	None	None
<i>Requirements for All Grades</i>					
VOLATILITY					
Density at 15°C, kg/m ³				Report	D 1298 or D 4052
Distillation, °C					D 86
Initial Boiling Point				Report	
Fuel Evaporated					
10% by Volume	Max		75		
40% by Volume	Min		75		
50% by Volume	Max		105		
90% by Volume	Max		135		
Final Boiling Point	Max		170		
Sum of 10% + 50% Evaporated Temperatures	Min		135		
Recovery % by Volume	Min		97		
Residue % by Volume	Max		1.5		
Loss % by Volume	Max		1.5		
Vapor Pressure, 38°C, kPa			38.0-49.0		D 323, D 5190 or D 5191 ⁸
FLUIDITY					
Freezing Point, °C	Max		-58		D 2386
COMPOSITION					
Sulfur, % by Mass	Max		0.05		D 1266 or D 2622
Net Heat of Combustion MJ/kg ⁹	Min		43.5		D 4529 or D 3338
CORROSION					
Corrosion, Copper Strip, 2 hr at 100°C	Max		No. 1		D 130

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Table 1-1. U.S. Commercial Aviation Gasoline Specifications – Grades 80, 91, 100LL, and 100 (Continued)

<i>Property</i>	<i>Requirements for All Grades</i>		<i>ASTM Test Method</i>
CONTAMINANTS			
Oxidation Stability (5h aging) ^{10,11}			D 873
Potential Gum, mg/100 mL	Max	6	
Lead Precipitate, mg/100 mL	Max	3	
Water Reaction			D 1094
Volume Change, mL	Max	± 2	
OTHER			
Electrical Conductivity, pS/m	Max	450 ¹²	D 2524

Data for this table was taken from ASTM D 910-03.

¹ A performance number of 130.0 is equivalent to a knock value determined using isoctane plus 0.34 mL TEL/L.

² Knock ratings shall be reported to the nearest 0.1 octane/performance number.

³ The maximum dye concentrations shown do not include solvent in dyes supplied in liquid form.

⁴ Essentially 1,4 dialkylamino-anthraquinone.

⁵ Essentially p-diethylaminoazobenzene (Color Index No. 11021) or 1,3-benzenediol 2,4-bis- [(alkylphenol)azo-].

⁶ Essentially alkyl derivatives of azobenzene-4-azo-2-naphthol.

⁷ Essentially benzene-azo-2-naphthol (Color Index No. 12055).

⁸ Test method D 5191 shall be the referee vapor pressure method.

⁹ For all grades use either Equation 1 or Table 1 in Test Method D 4529 or Equation 2 in Test Method D 3338. Test Method D 4809 may be used as an alternative. In case of dispute, Test Method D 4809 shall be used.

¹⁰ If mutually agreed between purchaser and supplier, a 16 hr aging gum requirement may be specified instead of the 5 hr aging gum test. In such case the gum content shall not exceed 10 mg/100 mL and the visible lead precipitate shall not exceed 4 mg/100 mL. In such fuel the permissible antioxidant shall not exceed 24 mg/L.

¹¹ Test Method D 381 existent gum test can provide a means of detecting quality deterioration or contamination, or both, with heavier products following distribution from refinery to airport.

¹² Applies only when an electrical conductivity additive is used. When a customer specifies fuel containing conductivity additive, the following conductivity limits shall apply under the conditions at the point of use: Minimum 50 pS/m, Maximum 450 pS/m. The supplier shall report the amount of additive used.

In 1998, ASTM published ASTM D 6227 Standard Specification for Grade 82 Unleaded Aviation Gasoline. Details are found in **Table 1-2**. Aviation Gasoline 82 UL is an aviation grade product which can be blended from automotive gasoline streams and is based on the requirements of piston engines designed and approved for such a fuel. This specification is intended to combine the necessary fuel quality of aviation gasoline with the high availability afforded by the automotive fuel streams. The specification requirements differ from those of ASTM D 910 Aviation Gasoline in distillation characteristics, oxygenate and TEL content, and vapor pressure limits. A purple color is used to identify the fuel.

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Table 1-2. U.S. Commercial Aviation Gasoline Specification – Grade 82 UL

Property	Requirement¹		ASTM Test Method
COMBUSTION			
Knock Value, Lean Mixture, Motor Method Octane Number	Min	82.0	D 2700
COLOR			
Color		Purple	D 2392
Dye Content ²			
Blue Dye, ³ mg/L	Max	7.5	
Red Dye, ⁴ mg/L	Max	1.9	
VOLATILITY			
Distillation			D 86
Distillation Temperature, °C (°F) at % Evaporated			
10% by Volume	Max	70 (158)	
50% by Volume		66 to 121 (150 to 250)	
90% by Volume	Max	190 (374)	
End Point	Max	225 (437)	
Residue, % by Volume	Max	2	
Distillation Recovery, % by Volume	Min	95	
Distillation Loss, % by Volume	Max	3.0	
Vapor Pressure, kPa (psi)		38 to 62 ⁵ (5.5 to 9.0)	D 4953, D 5190, D 5191, or D 482
Net Heat of Combustion, MJ/kg (BTU/lb)	Min	40.8 (17,540)	D 3338 ⁶ , D 4529 ⁶ , D 4809 ⁷
FLUIDITY			
Freezing Point, °C (°F)	Max	-58 (-72)	D 2386
CORROSION			
Copper Strip Corrosion, 3 hr at 50°C (122°F)	Max	No. 1	D 130
Sulfur, Mass %	Max	0.07	D 1266, D 2622, D 3120, D 294, D 5453
CONTAMINANTS			
Potential Gum, (5 hr aging), mg/100 mL ⁸	Max	6	D 873
COMPOSITION			
Lead Content, g/L (g/U.S. gallon)	Max	0.13 (0.05)	D 3237 or D 5059
Alcohols and Ether Content ⁹			D 4815, D 5599, or D 5845
Total Combined Methanol and Ethanol, % by Mass	Max	0.3	
Combined Aliphatic Ethers, Methanol and Ethanol, as % by Mass of Oxygen	Max	2.7	

Data for this table taken from ASTM D 6227-00

¹ The requirements stated herein are subject to rounding in accordance with Practice E 29 and are not subject to correction for tolerance of the test method.

² The maximum dye concentrations shown do not include solvent in dyes in liquid form.

³ Essentially 1,4 dialkylamino-anthraquinone.

⁴ Essentially alkyl derivatives of azobenzene-4-azo-2-naphthol.

⁵ Fuel with vapor pressure greater than 62 kPa (9.0 psi) is permissible, if the ambient temperature is not more than 29°C (85°F) at the time and place of delivery and as long as all federal and local regulations are met. The vapor pressure of permissible fuel exceeding 62 kPa (9.0 psi) shall be shown on all transfer documents, including the delivery document to the aircraft.

⁶ Use either Equation 1 or Table 1 in D 4529 or Equation 2 in D 3338.

⁷ D 4809 may be used as an alternative. In case of dispute, D 4809 shall be used.

⁸ D 381 existent gum test can provide a means of detecting deteriorated quality or contamination, or both, with heavier products following distribution from refinery to airport.

⁹ No deliberate addition of alcohol is allowed except for isopropyl alcohol that is allowed as an additive. (Refer to 6.2.4.2 in ASTM D 6227.)

United States Military Aviation Gasolines

The military specification for aviation gasoline, MIL-G-5572F, was withdrawn 22 March 1988, and is available from ASTM as Research Report (RR): D 02-1255 for historical review.

International Aviation Gasolines

British Ministry of Defence: Aviation Gasolines – The Defense Standard (Def Stan) 91-90 specification provides the requirements for three grades of aviation gasoline; AVGAS 80, AVGAS 100 and AVGAS 100LL. These aviation gasolines are nearly equivalent to the U.S. aviation gasolines per ASTM D 910 with the exception of a 2°C lower freezing point requirement, and a lower lead content in AVGAS 100 (0.85 vs. 1.12 g Pb/L).

As the North Atlantic Treaty Organization (NATO) military requirement for AVGAS declined, the F-18 NATO Code number designation was removed from AVGAS 100LL.

1.1.2 Turbine Fuel Specifications

Civil Aviation Turbine Fuel Specifications

Worldwide there are three major specifications in civil use, ASTM D 1655, the British Def Stan 91-91 and the Russian specification GOST 10227. Of these, only the ASTM specification is controlled by a nonmilitary organization. The other specifications are issued by military organizations but approved by civil authorities. Details on all these specifications follow. Military fuel specifications are treated in a subsequent section.

United States Civil Turbine Fuels

The detailed requirements of U.S. civil aviation turbine fuels are defined by ASTM D 1655 and are found in **Table 1-3**. Two grades, Jet A and Jet A-1, are in the kerosine boiling range, while Grade Jet B is a blend of naphtha and kerosine with wider distillation limits. Jet B is therefore known as a *wide-cut* fuel. Grade Jet A has a boiling range of approximately 149° to 290°C and is in general use in the United States where the maximum freezing point limit is set at -40°C to increase availability. Except for a lower maximum freezing point of -47°C, Grade Jet A-1 has the same specification limits as Grade Jet A. Jet B is a wide-cut fuel, with a boiling range of approximately 60°C to 260°C, a flash point below ambient room temperature and a maximum freezing point of -50°C. Jet B is the civil version of military Grade JP-4, MIL-DTL-5624, but is rapidly disappearing from the market, except for some operations in Alaska and Northern Canada. In 2000, ASTM created a separate specification for Jet B, ASTM D 6615, Specification for Jet B Wide-Cut Aviation Fuel, which is identical in all respects to the Jet B grade in D 1655. The two fuel specifications will coexist until all engines, currently certified on D 1655, Grade Jet B, are also approved on D 6615. The Jet B grade will then be removed from ASTM D 1655. None of these fuels require the use of additives, but some additives may be added by the supplier at his discretion, while others can only be added by agreement with the purchaser or user. More details on additives are given in a later section.

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Table 1-3. U.S. Commercial Turbine Fuel Specifications – Jet A, Jet A-1, Jet B¹

Property		<i>Jet A</i>	<i>Jet A-1</i>	<i>Jet B</i>	<i>ASTM Test Method</i>
COMPOSITION					
Acidity Total (mg KOH/g)	Max	0.10	0.10	--	D 3242
Aromatics (% by Volume)	Max	25	25	25	D 1319
Sulfur Mercaptan (% by Weight)	Max	0.003 ²	0.003 ²	0.003 ²	D 3227
Sulfur Total (% by Weight)	Max	0.30	0.30	0.3	D 1266, D 1552, D 2622
VOLATILITY					
Distillation Temperature (°C)					D 86
10% Recovered	Max	205	205	--	
20% Recovered	Max			145	
50% Recovered	Max	Report	Report	190	
90% Recovered	Max	Report	Report	245	
Final Boiling Point	Max	300	300	--	
Residue (% by Volume)	Max	1.5	1.5	1.5	
Loss (% by Volume)	Max	1.5	1.5	1.5	
Flash Point (°C)	Min	38 ³	38 ³		D 56 or D 3828 ⁴
Density at 15°C (kg/m ³)		775 to 840	775 to 840	751 to 802	D 1298 or D 4052
Vapor Pressure, 38°C (kPa)				14 to 21	D 323 or D 5191
FLUIDITY					
Freezing Point (°C) ⁵	Max	-40	-47	-50	D 2386 or D 5972 ⁶
Viscosity at -20°C (cSt) ⁷	Max	8.0	8.0	--	D 445
COMBUSTION					
Net Heat of Combustion ⁸	Min	42.8	42.8	42.8	D 4529, D 3338 or D 4809
<i>One of the following requirements shall be met</i>					
Smoke Point, mm	Min	25	25	25	D 1322
Smoke Point, mm and Naphthalenes (% by Volume)	Min	18	18	18	D 1322
Naphthalenes (% by Volume)	Max	3.0	3.0	3.0	D 1840
CORROSION					
Copper Strip (2 hrs at 100°C)	Max	No. 1	No. 1	No. 1	D 130
STABILITY					
Jet Fuel Thermal Oxidative Tester 2.5 hr at Control Temperature of 260°C					D 3241
Filter Pressure Drop (mm Hg) ⁹	Max	25	25	25	
Tube Deposit ¹⁰ Rating	Max	< 3, No peacock or abnormal color deposits	< 3, No peacock or abnormal color deposits	< 3, No peacock or abnormal color deposits	
CONTAMINANTS					
Existent Gum (mg/100 mL)	Max	7	7	7	D 381
Water Reaction Interface	Max	lb	lb	lb	D 1094
ADDITIVES¹¹					
Electrical Conductivity (pS/m) ¹²		-- ¹³	-- ¹³	-- ¹³	D 2624

¹ The data in this table was taken from ASTM Specification D 1655-02.

² The mercaptan sulfur determination may be waived if the fuel is considered sweet by the doctor test described in Test Method D 4952.

- ³ A higher minimum flash point specification may be agreed upon between purchaser and supplier.
- ⁴ Results obtained by Test Method D 3828 may be up to 2°C lower than those obtained by Test Method D 56, which is the preferred method. In case of dispute, Test Method D 56 will apply.
- ⁵ Other freezing points may be agreed to between supplier and purchaser.
- ⁶ Test Method 5972 may produce a higher (warmer temperature) than that from Test Method D 2386 on wide-cut fuels such as Jet B or JP-4. In case of dispute, D 2386 shall be the referee method.
- ⁷ 1 mm²/s = 1 cSt
- ⁸ For all grades use Equation 1 or Table 1 in Test Method D 4529 or Equation 2 in Test Method D 3338. Test Method D 4809 may be used as an alternative. In case of dispute Test Method D 4809 shall be used.
- ⁹ Preferred SI units are 3.3 kPa, maximum.
- ¹⁰ Tube deposits shall always be reported by the Visual Method; a rating by the Tube Deposit Rating (TDR) optical density method is desirable, but not mandatory.
- ¹¹ For detailed additive requirements refer to ASTM D 1655 and D 6615.
- ¹² 1 pS/m = $1 \times 10^{-12} \Omega^{-1} m^{-1}$
- ¹³ If electrical conductivity additive is used, the conductivity shall not exceed 450 pS/m at the point of use of the fuel. When electrical conductivity additive is specified by the purchaser, the conductivity shall be 50 to 450 pS/m under the conditions at the point of delivery.

British Civil Turbine Fuels

As indicated earlier, the specification for civil turbine fuel is issued by the Ministry of Defence as a specification with a military designation, now Def Stan 91-91 (formerly DERD 2494). This fuel grade carries the designation of AVTUR (or Jet A-1). The specification covers the requirements of one grade of kerosine type with a freezing point of -47°C maximum and a flash point of 38°C minimum. The use of antioxidants is required for fuels that have been hydroprocessed, and an antioxidant must be added immediately following hydroprocessing and prior to the product being passed into storage. Static dissipator must be added to the fuel. Metal deactivators, corrosion inhibitors, and fuel system icing inhibitor (FSII) may be used. As in other specifications, additive type and concentration must be reported. The grade Jet A-1 in the IATA Guidance Material (**Table 1-4**) is based largely on Def Stan 91-91 and ASTM D 1655.

Russian Civil Turbine Fuels

Russian turbine fuels for civil aviation are specified in GOST 10227, where Grades TS-1 (regular and premium) and Grade RT are the fuels of interest. The main specification differences between TS-1/RT and Western fuels are the lower fuel freezing point, flash point and viscosity, necessitated by the extreme cold encountered within Russia. Thus the specification freezing point of both TS-1 and RT fuels is -50°C, but this limit can be lower depending on the region of use and time of year. The limiting freezing point for TS-1 is -60°C and for RT is -55°C as compared to the -47°C freezing point of Jet A-1. Both Russian fuels have lower viscosities than Jet A-1. Viscosity specification limits are 8 cSt at -40°C for TS-1 and 16 cSt at -40°C for RT, while Western fuels have a maximum viscosity limit of 8 cSt at -20°C. Russian minimum flash points are 28°C against 38 or 40°C for Western fuels. Other differences involve differing test methods, the most important being thermal stability (TS). TS-1 fuel thermal stability is measured by a static method, GOST 11802, rather than a dynamic method such as ASTM D 3241 (JFTOT). A current research program is designed to establish the relationship between the two methods. More details on the TS-1 specification will be found in **Table 1-4**.

Grade TS-1 is the most widely used fuel for civil aircraft. Grade RT is formulated for subsonic engines, and supersonic engines with limited flight duration. Although not thought to be produced in large volume, Grade RT is occasionally found to be available fuel at Russian airports. Additives in Russian fuels are discussed later in the Additives section. In the latest development, Russian authorities have agreed to supply Jet A-1 meeting Western specifications at a number of Russian airports.

Table 1-4. IATA Guidance Material – Detailed Requirements of Aviation Turbine Fuels-Grades Jet A, Jet A-1, TS-1, Jet B

Property	JET A		JET A-1		TS-1		JET B		Notes
	Limits	Test Method(s)	Limits	Test Method(s)	Limits	GOST Test Method(s)	Limits	Test Method(s)	
APPEARANCE	Clear bright and visually free from solid matter and undissolved water at normal temperature								1
COMPOSITION									
Total Acidity, mg KOH/g (Max)	0.10	D 3242	0.015	IP354/D 3242	NA		0.10	D 3242	
mg KOH/100 mL (Max)	NA		NA		0.7	5985	NA		2
Aromatics, % by Volume (Max)	25.0	D 1319	25.0	IP156/D 1319	22.0	6994	25.0	D 1319	3
Olefins, % by Volume (Max)	NA		NA		NA		5.0	D 1319	
Sulphur, Total, % by Mass (Max)	0.30	D 4294 D 1266 D 2622 D 1552 D 5453	0.30	IP336 IP107 IP243 IP373 D 1266 D 1552 D 2622 D 4294 D 5453	0.25	19121	0.40	D 4294 D 1266 D 2622	
Sulphur, Mercaptan, % by Mass (Max) <i>or Doctor Test</i>	0.0030 Negative	D 3227 D 4952	0.0030 Negative	IP342/D 3227 IP30/D 4952	0.0050	17323	0.0030 Sweet	D 3227 D 4952	4
Iodine Number, g 1/100g (Max)	NA		NA		3.5	2070	NA		5
Refining Components, at Point of Manufacture									
Hydroprocessed Components, % by Volume	NA		Report		NA		NA		6
Severely Hydroprocessed Components, % by Volume	NA		Report		NA				
Lubricity Wear Scar Diameter, mm (Max)	NA		0.85	D 5001	NA		NA		7
VOLATILITY									
Distillation		D 86		IP123/D 86		2177		D 86	8
Initial Boiling Point, °C (Max)	NA		Report		150		Report		
Fuel Recovered					--				
10% by Volume at °C	205 (Max)		205 (Max)		165 (Max)		Report		
20% by Volume at °C	NA		NA		NA		90 to 145		

NA - Not Applicable

Table 1-4. IATA Guidance Material – Detailed Requirements of Aviation Turbine Fuels-Grades Jet A, Jet A-1, TS-1, Jet B (Continued)

Property	JET A		JET A-1		TS-1		JET B		Notes
	Limits	Test Method(s)	Limits	Test Method(s)	Limits	GOST Test Method(s)	Limits	Test Method(s)	
50% by Volume at °C	Report		Report		195 (Max)		110 to 190		
90% by Volume at °C (Max)	Report		Report		230		245		
End Point, °C (Max)	300		300		250 (98%)		Report		
Residue, % by Volume (Max)	1.5		1.5		NA		1.5		
Loss, % by Volume (Max)	1.5		1.5		NA		1.5	--	
Vapor Pressure, kPa (Max)	NA		NA		NA		21	D 323/D 5191	
Flash Point, °C (Min)	38	D 56/D 3828	38.0	IP170, IP 303 D 3828, D 56	28	6356	NA		9
Density at 15°C, kg/m ³	775-840	D 1298/D 4052	775-840	IP160/D 1298	NA	NA	750-801	D 1298/D 4052	
Density at 20°C, kg/m ³ Min	NA		NA	NA	775	3900	NA		10
FLUIDITY									
Freezing Point, °C (Max)	-40	D 2386/D 5972	-47.0	D 5972	NA		-51	D 2386/ D 5901/D 5972	
Chilling Point, °C (Max)					-50	5066 Method B			11
Viscosity at -20°C, mm ² /sec (Max)	8.0	D 445	8.0	IP71/D 445	NA		NA		12
Viscosity at 20°C, mm ² /sec (Min)	NA		NA		1.25	33	NA		
Viscosity at -40°C, mm ² /sec (Max)	NA		NA		8.0	33	NA		
COMBUSTION									
Net Heat of Combustion, MJ/kg (Min)	42.8	D 4809	42.8	IP381/D 4529	42.9	21261	42.8	D 4809	
		D 4529		IP12		11065		D 4529	
		D 3338		IP355				D 3338	
				D 4809					
				D 3338					
Smoke Point, mm (Min)	25	D 1322	25	IP57/D 1322			25	D 1322	
Height of Smokeless Flame (Min) or Smoke Point, mm (Min) and	18	D 1322	19	IP57/D 1322	25	4338	20	D 1322	

NA - Not Applicable

Table 1-4. IATA Guidance Material – Detailed Requirements of Aviation Turbine Fuels-Grades Jet A, Jet A-1, TS-1, Jet B (Continued)

Property	JET A		JET A-1		TS-1		JET B		Notes
	Limits	Test Method(s)	Limits	Test Method(s)	Limits	GOST Test Method(s)	Limits	Test Method(s)	
Naphthalenes, % by Volume (Max)	3.0	D 1840	3.0	D 1840	NA		3.0	D 1840	
CORROSION									
Corrosion, Copper Classification		D 130		IP154/D 131		6321		D 130	
(2 hr at 100°C) (Max)	No. 1		No. 1		NA		No. 1		
(3 hr at 100°C) (Max)	NA		NA		PASS				
Hydrogen Sulphide (Max)	NA		NA		NIL	17323	NA		14, 15
STABILITY									
Thermal Stability (JFTOT)		D 3241		IP323/D 3241				D 3241	
Control Temperature, °C	260		260				260		
Filter Pressure Drop, mm Hg (Max)	25		25		NA		3.4 kPa		16
Tube Deposit Code Rating (Visual) (Max)	<3, No Peacock or Abnormal Color Deposits		<3, No Peacock or Abnormal Color Deposits		NA		<3, No Peacock or Abnormal Color Deposits		
Thermal Stability, Static Test 150°C, 4 hr, mg/100 mL (Max)	NA		NA		18	11802	NA		
CONTAMINANTS									
Existent Gum, mg/100 mL (Max)	7	D 381 D 1094	7	IP131/D 381	5	1567		NA	17
Water Reaction				IP289/D 1094		27154		D 1094	
Interface Rating (Max)	1b		1b		1		1b		
Separation Rating, (Max)	NA		NA		1		NA		
Microseparometer (MSEP) Rating	NA								18
With Static Dissipator Add. (Min)	NA		70	D 3948	NA		70	D 3948	19
Without Static Dissipator Add. (Min)	NA		85		NA		NA		
Ash Content, % by Mass (Max)	NA		NA		0.003	1461	NA		20
Water Soluble Acids and Alkali (Max)	NA		NA		NIL	6307	NA		20

NA - Not Applicable

Table 1-4. IATA Guidance Material – Detailed Requirements of Aviation Turbine Fuels-Grades Jet A, Jet A-1, TS-1, Jet B (Continued)

Property	JET A		JET A-1		TS-1		JET B		Notes
	Limits	Test Method(s)	Limits	Test Method(s)	Limits	GOST Test Method(s)	Limits	Test Method(s)	
Soaps of Naphthenic Acids (Max)	NA		NA		NIL	21103	NA		20
Particulate Matter, mg/L, at Time of Delivery	NA			IP216/D 2276		10577		D 2276	21
Aircraft and Refuelers (Max)			See Part III Guidance Material		3		0.44	D 5452	
Purchaser's Storage (Max)	NA		NA		NA		2.2	D 2276/D 5452	
CONDUCTIVITY									
Electrical Conductivity, pS/m									
At Aircraft Fueling (Min)	NA		NA		50	25950	NA		22
At 20°C (Max)	NA		NA		600	25950	NA		
At Point of Use (Max)	450	D 2624	NA		NA		NA		
At Time and Temperature of Custody Transfer	NA		50-450	IP274/D 2624	NA		50-500	D 2624	
ADDITIVES									
Antioxidant mg/L (Optional) (Max)	24		24		24-32		25		23
	NA		17-24				NA		
In Hydroprocessed Portion (Mandatory)									
Hydroprocessed Fuel in Batch, % by Volume	NA		Report		NA		NA		
Non-Hydroprocessed Fuels (Optional) mg/L (Max)	NA		24.0		NA		NA		
Metal Deactivator, mg/L (Optional) (Max)	5.7				NA		5.7		24
On Initial Treatment When Batching (Max)			2.0						
Cumulative Concentration (Max)			5.7						
Static Dissipator, mg/L	Optional		Mandatory		By Agreement		Mandatory		25
First Doping, STADIS 450 (Max)	3		3				3		
Sigbol (Max)	NA		NA		4		NA		26
Cumulative, STADIS 450 (Max)	5		5		NA		5		

NA - Not Applicable

Table 1-4. IATA Guidance Material – Detailed Requirements of Aviation Turbine Fuels-Grades Jet A, Jet A-1, TS-1, Jet B (Continued)

<i>Property</i>	<i>JET A</i>		<i>JET A-1</i>		<i>TS-1</i>		<i>JET B</i>		<i>Notes</i>
	<i>Limits</i>	<i>Test Method(s)</i>	<i>Limits</i>	<i>Test Method(s)</i>	<i>Limits</i>	<i>GOST Test Method(s)</i>	<i>Limits</i>	<i>Test Method(s)</i>	
Icing Inhibitor, % by Volume (by Agreement) (Min)	0.10	D 5006	0.10	IP424	0.1		0.10	D 5006	27
Icing Inhibitor, % by Volume (by Agreement) (Max)	0.15		0.15	D 5006	0.3		0.15	IP424	
Corrosion Inhibitor/Lubricity Additive (by Agreement)									28

NA - Not Applicable

Reference – IATA GM

The specifications shown in **Table 1-4** are incomplete and may be obsolete. The most recent revision of the specification must be obtained for anything other than a cursory review of fuel property requirements.

Notes to Table 1-4

1. ASTM D 4176 Procedure 1 can be used to determine appearance.
2. The acidity of TS-1 shall not exceed 0.7 mg KOH/100 mL. This is converted to 0.009 mg KOH/g by assuming a fuel density of 800 kg/m³ at 15°C (59°F).
3. Aromatics content of less than 8 percent by volume may affect elastomer life and integrity and give possible seepage of fuel past the O-rings in engine and aircraft fuel systems, depending on the type of aromatic compounds present, and the condition, materials of construction, and past exposure of elastomer components.
4. GOST 10227 does not have a qualitative test such as ASTM D 4952 or IP342 (Doctor Test) to evaluate mercaptan content of TS-1 fuel.
5. Iodine number limits the olefin content of TS-1. Olefin content is used in the calculation of aromatics content in TS-1 according to GOST 6994. Olefin content of Jet A and Jet A-1 is controlled by the thermal stability and existent gum requirements.
6. Severely hydroprocessed components are defined as petroleum derived hydrocarbons that have been subjected to a hydrogen partial pressure of greater than 7000 kPa (70 bar or 1015 psi) during manufacture. This requirement comes into effect on 1 December 2000.
7. This requirement comes into effect on 1 December 2000. The lubricity requirement applies only to fuel containing more than 95 percent hydroprocessed material where at least 20 percent of this is severely hydroprocessed, and for all fuels containing synthetic components. This limit applies only at the point of manufacture.
8. Differences in boiling ranges are a fundamental distinction between fuel grades Jet A and Jet A-1 compared to TS-1 and to Jet B. The boiling range requirements for Jet B are being revised by CGSB ballot action to be compatible with other wide-cut fuel specifications.
9. According to GOST 6356, with the minimum flash point of 28°C (82°F), TS-1 has approximately an ASTM D 56 Tag Closed cup flash point of 31 to 33°C (87 to 91°F). When ASTM D 56 is used to determine flash point of Jet A-1, a minimum limit of 40°C (104°F) applies. Fuel having a D 56 flash point of 40°C (104°F) will have a D 3828 or IP170 flash point of 38°C (100°F).
10. The lower maximum distillation end point and aromatics content permitted for TS-1 limits maximum density, thus a density greater than the 840 kg/m³ maximum permitted for Jet A and Jet A-1 is very unlikely.
11. A maximum TS-1 chilling point of -55°C (-72°F) or -60°C (-76°F) can be required by the purchaser for operation from climatic zones where ambient ground temperatures may be less than -30°C (-22°F) during the 24 hour period before takeoff. However, most fuel is produced with a maximum chilling point of -50°C (-58°F). Differences in test methods are such that TS-1 with a -50°C (-58°F) chilling point according to GOST 5066 Method B will probably have a -47°C (-53°F) freezing point according to IP16/ASTM D 2386. When using ASTM D 4305 for Jet A or Jet A-1, use Procedure A only, do not use Procedure B. ASTM D 4305 shall not be used on samples with viscosities greater than 5.0 mm²/sec at -20°C (-4°F); if the viscosity cannot be obtained via the batch certificate(s), then it shall be measured.

12. Many engine and auxiliary power unit manufacturers specify a maximum viscosity of 12 mm²/sec to ensure satisfactory low temperature engine starting. Requirements for TS-1 are more restrictive than for Jet A and Jet A-1 and an advantage for operation in cold regions. The viscosity of Jet B is not specified because its boiling range assures a satisfactory low viscosity even at extremely low temperatures.
13. The JCL cites this property as specific energy instead of net heat of combustion. Specific energy and net heat of combustion are determined by the same methods, and results are equivalent.
14. Silver corrosion requirements will be phased out of the Jet B specification in the next edition of CAN/CGSB 3.22 because of the very small population of fuel pumps that still contain silver parts.
15. The TS-1 requirement for a negative result for hydrogen sulphide may help give the same information as the silver corrosion test. Hydrogen sulphide also attacks copper but the silver strip test method is sensitive to lower concentrations.
16. ASTM D 3241 test (JFTOT) shall be conducted for 2.5 hours at a test temperature of 260°C (500°F) for Jet A, Jet A-1, and Jet B. Thermal stability test methods are a major difference between TS-1 and the other fuel grades, and correlation is being studied. Tests show that most fuels pass both GOST 11802 and D 3241. GOST 10227-86 requires that thermal stability be determined by the dynamic test method, GOST 17751 not less than every three months during production of fuel batch.
17. While ASTM D 381 requires use of steam for evaporation of jet fuel, it is known that air is frequently substituted. Only steam shall be used for the evaporation of Jet A-1. This practice of using air for Jet A is accepted because data shows that the use of air typically increases the level of existent gum determined by the method, compared to use of steam.
18. Jet A has no ASTM D 3948 MSEP requirement because of the complexity of the U.S. distribution system, with frequent changes of custody before delivery to the airport. There is no related method for TS-1.
19. Jet A-1 ASTM D 3948 MSEP rating requirement applies only at the point of fuel manufacture. The Jet B MSEP rating requirement applies until the point where fuel enters dedicated aviation fuel storage.
20. TS-1 requirements for ash content, water-soluble acids and alkali, and soaps of naphthenic acids remain in GOST 10227 from earlier days and are properties not perceived necessary for the other fuel grades. Determination of soaps of naphthenic acids is only required if fuel has been caustic and water washed. The sensitivity of the test methods to the presence of surfactants that might disarm filter coalescers is not known.
21. Particulate matter requirements for Jet A-1 are discussed in Part III of the GM. These requirements apply at airports being audited by IATA Inspection Teams or representatives.
22. Maximum conductivity limits in all grades are intended to minimize effects on aircraft fuel quantity gauges still found in older aircraft. When additive depletion is evident by conductivity loss, further addition may be made to bring Jet A, Jet A-1 or Jet B into the acceptable conductivity range, provided the cumulative total dosage of STADIS 450 does not exceed 5 ppm.
23. Antioxidant is mandatory in the hydrogen-treated portion of Jet A-1 fuel, and is a supplier option in Jet A-1 fuel that is not hydrogen-treated. If all of the components in a batch have not been hydrogen treated, then the hydrogen treated portion of Jet A-1 must be reported. Antioxidant is a supplier option in Jet A and Jet B. The requirement for use of antioxidant in TS-1 is established by the Department of Civil Aviation and the refinery's technical requirements. Only approved antioxidants may be used; see Part II, Additives, of the GM.
24. There is no option to use metal deactivator additive in TS-1 fuel. The concentration of metal deactivator additive in Jet A-1 may not exceed 2.0 mg/L at time of initial batching.

25. Conductivity limits are mandatory to meet the requirements for Jet A-1. However, jet fuel may be certified at the refinery without static dissipator additive, and the additive added further downstream. In such cases the certificate of quality should then state: *Product meets requirements of Defence Standard 91-91, except for electrical conductivity.* Such fuel must meet the mandatory conductivity requirements at the point of delivery into aircraft.
26. Sigbol is normally not present in TS-1 supplied at major international airports. If the initially added concentration of STADIS™ 450 is not known, a maximum of 2 mg/L may be added later.
27. FSII are not permitted unless approved by the user.
28. Corrosion Inhibitors are not permitted unless approved by the user. See Part II, *Additives*, of the GM.

Canadian Civil Turbine Fuels

In Canada, aviation turbine fuel kerosine is covered by specification CAN/CGSB 3.23, which includes two grades of kerosine, Jet A and Jet A-1. The two grades only differ in freezing point requirements, with a maximum freezing point of -40°C for Jet A and -47°C for Jet A-1. Jet A and Jet A-1 will be seen to have similar specifications to their ASTM counterparts, but, unlike the US, Jet A-1 is the predominant fuel produced in Canada.

Canadian Wide-Cut Turbine Fuel

The Canadian specification for wide-cut turbine fuel is CAN/CGSB 3.22. This standard includes two grades of aviation turbine fuel, Jet B being commercial while Grade F-40 is military. Jet B has continued in limited use, particularly in extreme Northern areas. However, in 2000 the Canadian government announced its intention to phase out both fuels by the end of 2002. Jet B would be available in drum quantities through 2003. This action has been carried through.

People's Republic of China Aviation Turbine Fuel

The Chinese civil aviation fuel is described by specification GB 6537, No. 3 Jet Fuel. This specification is based on the Joint Fueling System Guide List which combines the requirements of Def Stan 91-91 and ASTM D 1655, Grade Jet A-1. The product compares very well to Jet A-1 fuels produced in other parts of the world. No. 3 Jet Fuel is found in the major international airports such as Beijing, Shanghai, and Guangzhou. Fuel meeting the Chinese version of Russian TS-1 specifications may be found in cities without international flights.

Romanian Fuels

Romanian fuel STAS 5639, grade TH, is a hydrotreated kerosine fuel. Deviations in the TH grade as compared to ASTM D 1655 and Def Stan 91-91 include a lower flash point, higher mercaptan sulfur content, lower distillation end point, and the use of the obsolete ASTM Coker test (ASTM D 1660) for fuel thermal stability versus the JFTOT (ASTM D 3241). These characteristics allow a lower maximum freezing point than Jet A-1. Because the TH fuel is hydrotreated, the use of an oxidation inhibitor additive is required. STADIS 450 is specified as the conductivity improver additive.

Combined Industry Specifications

Joint Fuelling Systems Check List

For purposes of international standardization eight international oil companies have created and maintain the Aviation Fuel Quality Requirements for Jointly Operated Systems (AFQRJOS), also referred to as Joint Fuelling Systems Check List (JFSCL) or plain Joint Check List. This check list combines the most restrictive limits of the latest ASTM Grade Jet A-1 and Def Stan 91-91 and is used in joint operations of three or more fuel companies outside the U.S. Its use ensures that the product meets the requirements of Western airlines.

IATA Guidance Material

For the benefit of its member airlines, the International Air Transport Association (IATA) has issued a guidance material (GM) document that can be used by the individual members in fuel purchase contracts. The document covers four fuel grades:

- Jet A meeting the requirements of ASTM D 1655.
- Jet A-1 meeting the requirements of ASTM D 1655 and Def Stan 91-91 (the Joint Check List).
- TS-1 meeting the requirements of GOST 10227, originating in Russia and the Commonwealth of Independent States.
- Jet B meeting the requirements of Canadian Specification CAN/CGSB 3.22.

Details of specifications covered by the IATA document can be reviewed in **Table 1-4**. TS-1 fuel is qualified using Russian test procedures as defined in GOST 10227. As noted in the previous section some GOST test methods are significantly different from those used in ASTM or Def Stan, so the limits for several fuel properties cannot be compared directly.

At the time of this writing, Russian authorities announced their intention to manufacture jet fuel to Western Jet A-1 standards. Initially such fuel will be limited to international airports. TS-1 will be supplied in the interim.

It is also expected that Jet B will be eliminated from the next issue of the IATA Guidance Material for Aviation Turbine Fuel.

Military Turbine Fuels

United States Military Turbine Fuels

There are three standard turbine fuels and two specialty fuels in use by the U.S. military services. The specifications for the standard turbine fuels (JP-4, JP-5, and JP-8) are located in **Table 1-5**. The specialty turbine fuels (JP-7 and JP-TS) will be found in **Table 1-6**. The corresponding NATO designations for these and other fuel specifications are listed in **Table 1-7**. Specifications having the same NATO number are fully coordinated so that the NATO numbers allow a ready comparison between the military specifications of several countries.

JP-4, per MIL-DTL-5624, and designated as NATO F-40, is a wide-cut type, low flash point turbine fuel that is essentially Jet B with a military additive package. Because of its higher volatility JP-4 fueled engines were generally easier to start at very low temperatures such as encountered in the arctic and at high altitudes. However, the higher volatility resulted in ground handling and aerial safety problems, such as fires after fuel spills or low velocity crashes. The DoD replaced JP-4 with JP-8 in the late 1980s and JP-4 is no longer routinely purchased.

JP-5, per MIL-DTL-5624 and designated NATO F-44, is designed by the U.S. Navy to meet operational safety requirements, especially on board of aircraft carriers. JP-5, therefore, is a high flash point, low freezing point kerosine. The higher flash point, together with the low freezing point, are met by reducing the distillation range compared to Jet A or Jet A-1 and result in a product of limited availability precluding its general use throughout the U.S. military services.

JP-8, per MIL-DTL-83133 is based on the civil fuel, Jet A-1, but requires specific additive packages. F-34 (JP-8) contains a static dissipator additive, a corrosion inhibitor/lubricity improver additive and FSII additive. It may contain antioxidant and metal deactivator additives. F-35 contains a static dissipator additive, may contain antioxidant, corrosion inhibitor/lubricity improver and metal deactivator additives, but does not contain fuel system icing inhibitor additive. F-37 is F-34 with a thermal stability additive package (JP-8+100). By adopting diesel and turbine-powered ground equipment and eliminating gasoline-powered ground vehicles, the U.S. military is enabling JP-8 to become a single fuel for the battlefield. The latest variant of the JP-8 grade is JP-8+100, which is JP-8 containing a thermal stability additive. This fuel is discussed in greater detail in the section *Additives*.

JP-7, per MIL-DTL-38219, is a fuel with high thermal stability developed by the U.S. Air Force for use in the SR-71 and the YF-12. Released originally under the specification MIL-T-38219, it is a mixture of cycloparaffins and straight chain paraffins and contains a lubricity additive. Because of JP-7's low volatility, engines in these aircraft are started with tetra-ethyl boron.

JP-TS, Jet Propulsion Thermally Stable (JP-TS) per MIL-DTL-25524, was developed for the U-2 (TR-1) aircraft and has a low freezing point and high thermal stability. The U. S. Air Force is working to replace JP-TS with a modified JP-8+100 using additional additives which extend the low temperature operating range.

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Table 1-5. U.S. Military Specifications for Turbine Fuels – JP-4, JP-5, JP-8

Property		JP-4¹	JP-5¹	JP-8²	Test Method
COMPOSITION					
Acidity, Total (mg KOH/g)	Max	0.015	0.015	0.015	D 3242
Aromatics (% by Volume)	Max	25.0	25.0	25.0	D 1319
Sulfur, Mercaptan (% by Mass) <i>or</i> Doctor Test	Max	0.002 Negative	0.002 Negative	0.002 Negative	D 3227 D 4952
Sulfur, Total (% by Mass)	Max	0.40	0.40	0.30	D 129 (JP-8), D 1266, D 2887, D 2622, D 3120, D 4294, ³ or D 5453
Color, Saybolt		Report	Report	Report	D 156 or D 6045
VOLATILITY					
Distillation [D 2887 Limits in parentheses]					D 86 ^{3,4} or D 2887
Distillation Temperature, (°C)					
Initial Boiling Point	Max	Report	Report	Report	
10% Recovered	Max	Report	206 (185)	205 (186)	
20% Recovered	Min	100	Report	Report	
50% Recovered	Min	125	Report	Report	
90% Recovered		Report	Report	Report	
End Point Temperature	Max	270	300 (330)	300 (330)	
Residue (% by Volume) (for D 86)	Max	1.5	1.5	1.5	
Loss (% by Volume) (for D 86)	Max	1.5	1.5	1.5	
Flash Point (°C)	Min		60	38	D 56, D 93 or D 3828 ⁵
Density, 15°C (kg/m ³)		751-802	788-845	775-840	D 1298 or D 4052 ³
°API Gravity, (60°F)		45-57	36-48	37-51	D 1298
Vapor Pressure (37.8°C) kPa		14-21	–	–	D 323, D 4953, D 5190 or D 5191 ⁶
FLUIDITY					
Freezing Point, °C	Max	-58	-46	-47	D 2386, ³ D 5901 or D 5972 ⁷
Viscosity at -20°C (cSt)	Max	–	8.5	8.0	D 445
COMBUSTION					
Net Heat of Combustion, MJ/kg	Min	42.8	42.6	42.8	D 3338, ⁸ D 4809, ³ or D 4529 (JP-4 and JP-5)
Calculated Cetane Index			Report	Report	D 976 ⁹
Hydrogen Content (% by Mass)	Min	13.5	13.4	13.4	D 3701, ¹⁰ D 3343
Smoke Point (mm) <i>or</i>	Min	20.0	19.0	25.0	D 1322
Smoke Point (mm) <i>and</i>	Min	--	--	19.0	D 1322
Naphthalenes, vol %	Max			3.0	D 1840
CORROSION					
Copper Strip (2 hr at 100°C)	Max	1	1	1	D 130

Handbook of Aviation Fuel Properties

Table 1-5. U.S. Military Specifications for Turbine Fuels – JP-4, JP-5, JP-8 (Continued)

Property		JP-4¹	JP-5¹	JP-8²	Test Method
THERMAL STABILITY JFTOT					
Pressure Drop (mm Hg)	Max	25	25	25	D 3241 ¹¹
Tube Color Code	Max	< 3, No peacock or abnormal color. Such deposits result in failure	< 3, No peacock or abnormal color. Such deposits result in failure	< 3, No peacock or abnormal color. Such deposits result in failure	
CONTAMINANTS					
Existent Gum (mg/100 mL)	Max	7.0	7.0	7.0	D 381 ¹²
Particulates (mg/liter) ¹³	Max	1.0	1.0	1.0	D 2276 or D 5452 ³
Water Reaction Interface	Max	1b	1b	1b	D 1094
Water Separation Index	Min	70 ¹⁴	85 ¹⁵	70 ¹⁴	D 3948
Filtration Time (minutes)	Max	10	15	15	-- ¹³
ADDITIONS					
Anti-Icing (% by Volume)		0.10 to 0.15	0.15 to 0.20	0.10 to 0.15	D 5006 (DiEGME)
Antioxidant ¹⁶		Required	Required	Required	
OTHER					
Conductivity (pS/m)		150 to 600 ¹⁷		150 to 450 ¹⁸	D 2624

¹ Data for this fuel were taken from MIL-DTL-5624T.

² Data for this fuel were taken from MIL-DTL-83133E.

³ Referee method.

⁴ A condenser temperature of 0° to 4°C shall be used in the distillation of JP-5 and JP-8 fuels. For JP-4, group 3 test conditions shall be used.

⁵ ASTM 3828 may give results up to 1.7°C below the D 93 results. ASTM D 56 may give results up to 1.0°C below the D 56 results.

⁶ When using D 5191 for vapor pressure determination of JP-4, the quality checks, Section 10 of the specification, must be performed every day using two control samples as the reference pure materials. The first control sample must have a vapor pressure between 7 and 14 kPa and the second sample's vapor pressure must be between 21 and 23 kPa.

⁷ ASTM D 5972 may be used for freezing point determination of JP-5 and JP-8.

⁸ When the fuel distillation test is performed using D 2887, the average distillation temperature, for use in D 3338, shall be calculated as follows:

$$V = (10\% + 50\% + 95\%)/3$$

⁹ Mid-boiling temperatures may be obtained by either D 86 or D 2887 to perform the Cetane Index calculation. If D 86 values are used, they should be corrected to standard barometric pressure.

¹⁰ D 3343 or D 3701 may be used to measure hydrogen content of JP-4, but when measuring hydrogen content of JP-5, only D 3701 shall be used.

¹¹ See Section 4.5.3 of the JP-8 specification for ASTM D 3241 test conditions and test limitations.

¹² If air is used instead of steam while performing D 381, it must be reported. In case of failure with air, the sample must be retested with steam.

¹³ Minimum 3.79 L sample. Filtration time in accordance with Appendix A of MIL-DTL-5624. This procedure can also be used for D 2276 particulate.

¹⁴ With all additives except electrical conductivity additive.

¹⁵ With all additives except the corrosion inhibitor additive or 70 with all additives present.

¹⁶ If hydrogen treated blend stocks used; this is optional if no hydrotreating is used.

¹⁷ The conductivity must be in the range of 150 to 600 pS/m at ambient fuel temperature or 29.4°C, whichever is lower.

¹⁸ The conductivity must be in the range of 150 to 450 pS/m for F-34 (JP-8) and between 50 and 450 pS/m for F-35 at ambient fuel temperature or 29.4°C, whichever is lower. In the case of JP-8+100, the conductivity must be between 150 to 700 pS/m at ambient fuel temperature or 29.4°C, whichever is lower.

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Table 1-6. U.S. Military Specifications for Turbine Fuels – Grades JP-7, JP-TS

Property		JP-7¹	JP-TS²	Test Method
COMPOSITION				
Acidity, Total (mg KOH/g)	Max		0.015	D 3242
Aromatics (vol %)	Max	5	5.0 to 20.0	D 1319
Sulfur, Mercaptan (% by Mass) <i>or</i> Doctor Test	Max	0.001 Negative	0.001 Negative	D 3227 D 4952
Sulfur, Total (% by Mass)	Max	0.1	0.3	D 1266, D 2622 D 3120, D 4294, ³ or D 5453 ⁴
Color, Saybolt	Min		+24	D 156 ³ or D 6045
VOLATILITY				
Distillation Temperature °C (D 2887 limits in parentheses)				D 86 ⁵ or D 2887
Initial Boiling Point (°C)	Min	182	157 (105)	
10% Recovered (°C)		196 Min	193 (174) Max	
20% Recovered (°C)		206 Min ⁶		
50% Recovered (°C)	Max	Report	204 (207) Max	
90% Recovered (°C)	Max	260	238 (250)	
Final Boiling Point (°C)	Max	288	260 (288)	
Residue (vol %)	Max	1.5	1.5	D 86
Loss (vol %)	Max	1.5	1.5	D 86
Flash Point (°C)	Min	60	43	D 56, D 93, or D 3828
Density, 15°C (kg/L)		0.779 to 0.806	0.767 to 0.797	D 1298 or D 4052 ³
Vapor Pressure at 149°C (kPa)	Max	20.7 ⁷		
Vapor Pressure at 260°C (kPa)	Max	331 ⁷		
FLUIDITY				
Freezing Point (°C)	Max	-43.3	-53	D 2386 ³ or D 5972
Viscosity at -40°C (cSt)	Max.		12.0	D 445
Viscosity at -20°C (cSt) ⁸	Max	8.0		D 445
Viscosity at 34.5°C may be performed if a calibrated thermometer for -20°C is not available	Max.	15.0		D 445
COMBUSTION				
Net Heat of Combustion, MJ/kg	Min	43.5	42.8	D 2382, D 3338, D 4529, or D 4809
Smoke Point	Min		25.0	D 1322
Hydrogen Content (% by Weight %)	Min	14.40 ⁹	14.00	D 3343 or D 3701 ³
CORROSION				
Copper Corrosion (2 hr at 100°C)	Max	1b	1b	D 130
THERMAL STABILITY JFTOT				
JFTOT TDR	Max	12 ¹⁰	12 ¹¹	
Pressure Differential, mm Hg	Max	25 ¹⁰	25 ¹¹	
CONTAMINANTS				
Existent Gum (mg/100 mL)	Max	5.0	5.0 ¹²	D 381
Particulate Matter (mg/L)				
Origin	Max	0.3	0.3	D 2276 ¹³
Destination	Max	0.5	0.5	or D 5452 ¹³
Water Separatometer Index	Min	85	Report	D 3948

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Table 1-6. U.S. Military Specifications for Turbine Fuels – Grades JP-7, JP-TS (Continued)

Property		JP-7¹	JP-TS²	Test Method
Water Reaction Interface Rating	Max	lb	lb	D 1094
ADDITIVES				
JFA-5 (mg/L)			8.6 to 11.4	
Fuel System Icing Inhibitor, vol %		0.10 to 0.15	0.10 to 0.15	ASTM D 5006 FED-STD-791, methods 5327, 5340 or 5342 ¹⁴
Antioxidant		Required ¹⁵	Required ¹⁵	
Metal Deactivator		Option not to exceed 5.7 mg/L	Option ¹⁵	
Lubricity additive PWA-536 parts per million (ppm)		200 to 250	Required ¹⁵	

¹ Data for this table were taken from MIL-DTL- 38219D

² This material was taken from MIL-DTL-25524E.

³ Referee test method.

⁴ Allowed in MIL- DTL-25524.

⁵ A condenser temperature of 0° to 4.4 °C shall be used. To ensure accurate IBP data, the operator must cut back on the heating rate when the vapor/condensate ring rises to within 25 mm of the vapor tube. The reduced heating rate allows the thermometer to reflect more accurately the true vapor pressure when the first condensate is collected.

⁶ The temperature reading at the 20 percent recovered point shall be corrected for the emergent stem in accordance with ASTM E77, paragraph 7, *Treatment of Data*.

⁷ Vapor pressure test in accordance with Appendix A or C, MIL-DTL-38219.

⁸ Until an ASTM thermometer calibrated for the -20°C condition becomes available, this test may be conducted at -34.5°C with a maximum allowable viscosity of 15.0 cSt.

⁹ Mass hydrogen content may be calculated using ASTM D 3343 or measured using ASTM D 3701. In case of conflict, ASTM D 3701 shall apply.

¹⁰ Test by D 3241 – Conditions as specified in MIL-PRF-38219, 4.5.2.1.

¹¹ Test by D 3241 – Conditions as specified in MIL-DTL-25524, 4.5.2.1.

¹² If air is used instead of steam while performing ASTM D 381, it must be reported. In case of failure with air, the sample must be retested with steam.

¹³ Minimum sample size of 3.79 liters (1 gallon) shall be filtered.

¹⁴ Use the appropriate scale on the refractometer.

¹⁵ Refer to respective specification for type and quantity.

Table 1-7. Fuel Specifications Versus NATO Designations

United States Specifications	United Kingdom Specifications	Canadian Specifications	NATO Designation
MIL-DTL-5624 Grade JP-4	Def Stan 91-88 Grade Aviation Turbine Fuel-Wide-Cut (AVTAG)	CAN/CGSB 3.22 Grade F-40	NATO F-40
MIL-DTL-5624 Grade JP-5	Def Stan 91-86 Grade AVCAT	CAN/3-GP-24 Grade F-44	NATO F-44
MIL-DTL-83133 Grade JP-8	Def Stan 91-87 Grade Aviation Turbine Fuel (AVTUR)	CAN/CGSB 3.23 Grade F-34	NATO F-34
MIL-DTL-83133 Grade NATO F-35	Def Stan 91-91 Type Jet A-1	N/A	NATO F-35
MIL-DTL-83133 Grade JP-8+100	N/A	N/A	NATO F-37

British Military Turbine Fuels

Standard Military Aviation Turbine Fuel – Def Stan 91-87 covers a kerosine type, aviation turbine fuel meeting NATO F-34 and is designated as AVTUR/FSII, originally specified as DERD 2453. Def Stan 91-87 corresponds to MIL-DTL-83133, Grade JP-8. The fuel differs from F-35 in respect of a mandatory requirement for FSII, corrosion inhibitor, and static dissipator additives. The maximum freezing point is -47°C and the minimum flash point is 38°C. Because Def Stan 91-91 requires a different flash point method, this limit is equivalent to 40°C by the U.S. method. The presence of conductivity additive is required. The use of antioxidants is permitted, but is required when the fuel is hydroprocessed. This additive must be added immediately following hydroprocessing and before the fuel is moved to storage. Metal deactivator may be used. All additive types and concentrations must be declared.

High Flash Turbine Fuel – Def Stan 91-86 covers high flash aviation turbine fuel meeting NATO Code F-44 and is designated as AVCAT/FSII. (It was originally specified as DERD 2452.) The specification provides the requirements for one grade of high flash point kerosine, intended primarily for use in naval military aircraft and containing FSII and corrosion inhibitor as mandatory additives. The specified flash point is 61°C minimum and the freezing point is -47°C maximum. The use of antioxidants is permitted and required when the fuel is a hydroprocessed fuel. Metal deactivator and corrosion inhibitor may be used. This product corresponds to MIL-DTL-5624, Grade JP-5.

Canadian Military Turbine Fuels

Wide-Cut Turbine Fuel – The Canadian specification for a wide-cut turbine fuel is CAN/CGSB 3.22. This standard includes two grades of aviation turbine fuel, Jet B being commercial while Grade F-40 is military. Grade F-40 is equivalent to JP-4. Its freezing point maximum is -58°C. The use of antioxidants is permitted. Corrosion inhibitor and fuel system icing inhibitor are required. The use of metal deactivators is permitted as is static dissipator. Canada has been the major producer and user of wide-cut fuels. However, in 2002 Canada announced a program to phase out JP-4 fuel in favor of JP-8. The phase-out has been completed by the first quarter of 2003.

High Flash Turbine Fuel – Canada uses a high flash turbine fuel per 3-GP-24. The fuel is similar to JP-5 and as such, product quality parameters are influenced by International Military Standardization Agreements. Similar to other JP-5 fuels, the flashpoint is 60°C minimum; the freezing point is -46°C maximum. The use of antioxidants, static dissipator and FSII is required. If necessary, corrosion inhibitors per U.S. Military Specification MIL-PRF-25017 are permitted. A metal deactivator may be used.

JetA/A-1 Kerosine Fuel – Kerosine-type turbine fuel is covered by CAN/CGSB 3.23 meeting NATO F-34. The maximum freezing point is -47°C and the minimum flash point is 38°C. The use of antioxidant is allowed and is required when the fuel is hydroprocessed. Metal deactivator and corrosion inhibitor may be used. Conductivity additive and FSII are mandatory. All additives and their concentrations must be declared.

United States Missile Fuels

The missile fuels discussed in this handbook consist of pure hydrocarbons or mixtures of specific hydrocarbons for use in air breathing missile engines. Active grades include RJ-4 and JP-10.

United States Ramjet Missile Fuels – The RJ fuels were originally developed for ramjet powered missiles. RJ-4 was selected for most missile applications, notably the U.S. Navy TALOS, and is defined by the active military specification MIL-P-82522. RJ-5 was originally specified by the U.S. Air Force and flight-tested on the Advanced Strategic Air-Launched Missile (ASALM). RJ-5 was replaced by RJ-6 due to RJ-5's unsatisfactory low temperature properties. RJ-6 was intended for the U.S. Navy/U.S. Air Force Long Range Conventional Standoff Weapon (LRCSW). Neither RJ-5 nor RJ-6 are in active use. RJ-4 fuel properties are shown in **Table 1-8**.

United States Turbine Missile Fuels – JP-9 was a high specific energy fuel developed for the Air Launched Cruise Missile (ALCM). JP-10 is designed for the same application but meets the -65°F U.S. Air Force operation freezing point requirement. It has replaced JP-9. JP-10 is defined by military specification MIL-P-87107. **Table 1-9** outlines the current specification requirements for JP-10.

United States Kerosine Rocket Fuels – MIL-P-25576 covers a kerosine propellant fuel for rocket engines referred to as RP-1. Last revised with an amendment on 15 June 1982, RP-1 is used in rockets as both the propellant and as the hydraulic fluid. RP-1 properties are shown in **Table 1-8**.

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Table 1-8. U.S. Military Specifications for Missile Fuels – Grades RJ-4, RP-1

<i>Property</i>	<i>RJ-4¹</i>	<i>RP-1^{2,3}</i>	<i>Test Method</i>
COMPOSITION			
Exo- and Endo-Isomers of Tetrahydrodi (Methylcyclopentadiene) % by Weight	100		
Sulfur total Max, % by Weight	0.005	0.05	D 2622 or D 3120
Mercaptan sulfur Max, % by Weight		0.005 or Doctor Sweet	D 121 or D 1323
Aromatics Max, % by Volume		5.0	D 1319
Olefins Max, % by Volume		2.0	D 1319
VOLATILITY			
Distillation Temperature (°C)			
Initial Boiling Point	Report	Report	D 86
5% Recovered	Report		
10% Recovered Range		185 to 210	
50% Recovered	Report	Report	
90% Recovered	Report	Report	
Final Boiling Point Max	232	274	
Residue (vol %) Max	1.5	1.5	
Loss (vol %) Max	1.0	1.5	
Flash Point (°C)	60 to 79	43 Min	D 93
Density at 15°C, kg/L	0.915 to 0.930	0.801 to 0.815	D 1298
FLUIDITY			
Viscosity, Centistokes			D 445
at -30°F, Max		16.5	
at 118°C, Max	20.0		
Freezing point (°F), Max	-47	-36	D 2386
COMBUSTION			
Net Heat of Combustion, Min			D 2382 or D 240
MJ/kg (BTU/lb)		43.0 (18,500)	D 240 or D 2382
MJ/m ³ (BTU/gallon)	38,900 (139,500)		
Aniline-Gravity, Min ⁴		7200	D 611 or D 287
Aniline Point, °F		Report	D 611
STABILITY			
Potential Gum 16 hr aging, (mg/100 mL), Max	14		D 873, FED-STD-791, Method 3354 ⁵
Thermal Stability (JFTOT)			
Change in Pressure Drop, mm Hg, Max	10	-.6	D 3241
Heater Tube Deposit Visual Rating, Max	2	-.6	
Copper Strip Corrosion, 2 hr at 100°C, Max	lb	1	D 130

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Table 1-8. U.S. Military Specifications for Missile Fuels – Grades RJ-4, RP-1 (Continued)

Property	RJ-4¹	RP-1^{2,3}	Test Method
CONTAMINANTS			
Existent Gum (mg/100 mL)	5.0	7	D 381
Water Raction		-- ⁷	Method 3251, FED-STD-791
Particulate Matter, Max			D 2276
mg/L	1.0		
mg/gal		5.7 ⁸	
ADDITIVES			
Antioxidant (g/L)	0.5 to 1.0 ⁹		
Anti-Icing (volume %) ⁸	0.10 to 0.15 ¹⁰		D 5006 ¹¹
OTHER			
Visual Appearance, clear and bright	Pass		D 4176
Color, Saybolt, Min	+25		D 156
Smoke Point, mm, Min	25.0		D 1322

¹ Data for this fuel were taken from MIL-P-82522.

² Data for this fuel were taken from MIL-P-25576C, Amendment 2.

³ The specification for RP-1 (MIL-P-25576C) is under revision at the time of this writing (early 2003).

⁴ Defined as the product of aniline point in °F and gravity in °API.

⁵ When conducting referee test, Method 3354 shall be used.

⁶ Refer to MIL-P-25576 for testing and rating details.

⁷ Standing time after shaking shall be 2 hr.

⁸ Use 0.80 micron membrane filter.

⁹ The antioxidant shall be 2, 6 ditertiary-butyl-4-methylphenol. For further requirements refer to paragraph 4.8 of MIL-P-82522C.

¹⁰ Type and amount requirements listed in 3.3.1, MIL-P-87107.

¹¹ Use the EGME scale. Method 5327 of FED-STD-791 is also acceptable.

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Table 1-9. U.S. Military Specifications for Missile Fuel – Grade JP-10¹

<i>Property</i>	<i>Limits</i>	<i>ASTM Test Method</i>
COMPOSITION		
Chemical Analysis (% by Weight) ²		
Exo-Tetrahydro (Cyclopentadiene)	98.5 to 100	
Other Hydrocarbons, Max	1.5	
VOLATILITY		
Flash Point (°C), Min	54.4	D 56, D 93, ³ or D 3828
Density, kg/m ³ at 150°C	935 to 943	D 1298 or D 4052 ³
FLUIDITY		
Freezing Point (°C) Max	Report ⁴	D 2386, D 5901, D 5972
Viscosity Centistokes, Max at:		D 445
-54°C	40	
-18°C	10	
COMBUSTION		
Net Heat of Combustion, Min		D 240 or D 2382
MJ/kg (BTU/lb)	42.1 (18,100)	
MJ/m ³ (BTU/gal)	39,400 (141,500)	
STABILITY		
Thermal Stability (JFTOT)		D 3241 ⁵
Change in Pressure Drop (mm Hg), Max	10	
Heater Tube Deposit Rating, Max	Code 2	
CONTAMINANTS		
Existent gum, mg/100 mL, Max	5.0	D 381 ⁶
Particulates (mg/L), Max	1.0	D 2276 or D 5452
ADDITIVES		
Anti-Icing ⁷ (vol %)	0.10 to 0.15	D 5006 ⁸
Antioxidants (ppm) ⁹	90 to 110 (5)	
OTHER		
Color, Saybolt, Min	+25	D 156 ³ or D 6045

¹ Data for this table were taken from MIL-DTL-87107D.

² Test procedures outlined in Appendix A or B, MIL-DTL-87107.

³ Referee method.

⁴ Expected freezing point -79°C (-100°F).

⁵ Maximum heater tube temperature 300°C (572°F) at pressure of 3.43 mPa (500 psig) at flow rate of 3 L/min for 150 min.

⁶ If air is used instead of steam while performing ASTM D 381, it must be reported. In case of a failure with air, the sample must be retested with steam.

⁷ Fuel system icing inhibitor shall only be used at the request of the user. When requested by the user, the fuel system icing inhibitor shall conform to MIL-DTL-85470.

⁸ Test shall be performed in accordance with ASTM D 5006 using the diEGME scale of the refractometer.

⁹ Refer to specification for approved antioxidants.

1.1.3 Additives

Additives in aviation fuels are important fuel constituents serving specific functions. However, they must be approved by original equipment manufacturers and relevant authorities before they can be used in aviation fuels. They may be listed in the specification by composition or by their proprietary name. In all cases the specification or Qualified Products List (QPL) will give the maximum allowed dosage. Allowance may also exist for *redoping* in the field if the loss of a specific property requires re-addition. Specifications may require additives to be present but may also allow their use on an optional basis. Only additives listed in the specification are permitted. The type and amount must be reported. Some additives can be used in aviation gasoline as well as in turbine fuels. Others are specific to each fuel type. Reference to the specification will indicate which additives are approved for that specification.

Tetraethyl Lead Mix – Tetraethyl lead is used only in aviation gasoline; its purpose is to suppress combustion knock. In addition to tetraethyl lead the additive contains ethylene dibromide which acts as a lead scavenger by converting lead oxide to lead bromide or lead oxybromide. Because the oxide is a solid at cylinder exhaust temperatures it deposits on internal surfaces such as valves and spark plugs. The bromides, being in gaseous form, generally exit the engine in the exhaust gas. To identify a lead-containing product, a dye must be added to the fuel. Different colors are used to identify different grades of aviation gasoline. To simplify blending the dye and scavenger are combined with tetraethyl lead in *tetraethyl mix*.

Antioxidants – The main function of antioxidants is to prevent the formation of gums and peroxides which can cause rapid deterioration of nitrile rubber fuel system components. Severe hydrotreating or hydrocracking can remove natural antioxidants, increasing the propensity of fuels to form peroxides (see **Table 1-4**, Note 6). For this reason a number of specifications require the addition of an antioxidant after any hydrotreating. However, antioxidants are optional in ASTM D 1655 fuels. Military specifications require the addition of antioxidant because fuel may experience longer storage times. Antioxidants must be added immediately after hydrogen treating for maximum effectiveness. Recent coordination efforts have resulted in a single list of acceptable hindered phenol antioxidants in most Western military and civil specifications. These additives do not significantly affect high temperature oxidation and other additives are required for this purpose. Antioxidants are listed by generic chemical formulas.

Metal Deactivator Additive – Metal deactivator additive (MDA) is allowed in all Western turbine fuels. MDA is used primarily in those fuels that have been refined using a copper sweetening process or come into contact with copper or copper-containing metals during handling. This additive reacts with soluble copper and other metal compounds forming chelates, thus minimizing metal-catalyzed oxidation that degrades thermal stability. Current specifications list a single approved metal deactivator. There is no provision for use of metal deactivator in TS-1.

Fuel System Icing Inhibitors – FSII additives prevent the formation of ice when water comes out of solution at low temperatures. Ethylene glycol monomethyl ether (EGME) has also been found to be an effective barrier to microbiological growth. Diethylene glycol monomethyl ether (DiEGME) has replaced EGME due to environmental concerns over EGME, and EGME is no longer an approved additive. DiEGME is specified for most military turbine fuels. Both additives are approved for use in Jet B per CAN/CGSB 3.22. FSII is permitted in civil turbine fuels, but is required in aircraft which do not have on-board fuel filter heaters. Fuel system icing inhibitors are not highly soluble in hydrocarbon fuels, thus requiring special mixing procedures to achieve full dissolution. Undissolved FSII can damage elastomers and other materials in the aircraft. Achieving good mixing also requires that the additive have a low dissolved water content before use. Contact with water will extract these additives from fuels. These additives are covered by ASTM Specification D 4171 and MIL-I-27686 and MIL-I-85470, as well as Def Stan 68-252.

The Russian specification GOST 10227 specifies either 0.15 volume percent Fluid I (ethyl cellosolve, aka ethylene glycol monoethyl ether) or TGF (tetrahydrofurfuryl alcohol); or 0.3 volume percent I-M (1:1 Fluid I and methanol) or TGF-M (1:1 TGF and methanol) additives. These additives are polar compounds similar in chemical make-up to those of U.S. anti-icing additives and are introduced at similar concentrations. TS-1 can contain ethyl

cellusolve (Fluid I), an equal mixture of ethyl cellusolve and methanol (Fluid I-M), tetrahydrafurfuryl alcohol (additive TGF), or an equal mixture of tetrahydrafurfuryl alcohol and methanol (TGF-M). Fluid I-M is reported to be the most commonly used of these additives. Western aviation gasoline can be treated with isopropyl alcohol as well as the glycol ethers.

Corrosion Inhibitors/Lubricity Additives – These additives were initially intended to minimize rusting in steel product pipelines and fuel storage tanks. They were later found to improve the lubricity of fuels as well and for this reason they are mandatory in all military and some civil turbine fuels. The exact composition of these materials is proprietary, but they are controlled by the military documents MIL-PRF-25017 and QPL-25017 in the U.S. and by Def Stan 68-251 and QPL 68-251 in the UK. Testing by the U.S. Air Force indicated excessive levels are not beneficial and can deactivate filter/coalescers. Allowable concentrations are stated in the QPL for each approved additive. At the time of this writing such additives are recognized by ASTM D 1655 but are not listed as approved.

The Russian specification GOST 10227 references a lubricity additive being approved at 0.002 to 0.004 weight percent treatment rate. The additive is described as distillate petroleum acids (DNK).

Static Dissipator (Electrical Conductivity) Additive – Static dissipator or electrical conductivity additive is mandatory in JP-4, JP-8 and Def Stan 91-91 and may be added to aviation gasoline by choice. This is currently not required in fuels meeting D 1655. This additive increases electrical conductivity, thereby enhancing the relaxation of electrostatic charges and lessening the chance of hazardous static discharges. Western specifications currently approve only STADIS 450 for use in Jet A, Jet A-1, and Jet B fuels as well as aviation gasolines. To function, this additive is mildly surface active. However water settling and coalescer operation is satisfactory in the absence of other complicating factors. Fuel quantity gauges on older aircraft may give erroneous low readings if fuel conductivity exceeds specification maximums.

Russian fuels sometimes contain the static dissipater additive Sigbol, whose exact formulation is proprietary. Sigbol is believed to be an analog of ASA-3, previously manufactured by Shell. It is believed to be a solution of organometallic compounds and polymers in hydrocarbon solvent, and has 2.0-3.5 percent ash. The maximum permitted concentration is 0.0005 weight percent.

Biocides – Biocides are used to kill microbiological growth in hydrocarbon fuels. ASTM D 1655 lists biocides as an acceptable additive class, with their use being subject to agreement by the purchaser. Biocides are not listed as acceptable additives in any other specifications referenced in the IATA Guidance Material. Some airframe and engine manufacturers have approved use of specific biocides on a case-by-case basis.

Due to the time required for treatment to be effective, biocides are typically used when an aircraft is left standing filled or partially filled with treated fuel. The fuel may then be used by the operator in accordance with both airframe and engine manufacturer's requirements. General biocide use in airport fuel delivery systems is prohibited.

ASTM D 6469, *Standard Guide for Microbial Contamination in Fuels and Fuel Systems*, provides information regarding biological contamination and its treatment. The guide is prepared specifically for individuals with limited microbiological background.

Leak Detection Additives – To locate leaks in underground jet fuel piping systems at airports, a process known as Tracer Tight™ may be used. In the process, an additive, Tracer A,™ (an extremely volatile chemical) is injected into the system and a chemical “sniffer” identifies leaks by signaling the presence of Tracer A outside the fuel system. This process allows finding and resolving underground jet fuel leaks with little or no impact on airline operations. Flight tests have demonstrated that the material quickly outgases from the fuel and causes no adverse affects to the propulsion system. Tracer A is listed in D 1655.

High Temperature Oxidative Stability Improver – High temperature oxidation stability is an important fuel property because jet fuel is the exchange medium for removing heat from engine oil, hydraulic fluid and avionics coolants. The fuel's high temperature oxidative stability and the heat path in the airframe and engine determine

whether fuel components will oxidize to form insoluble material which can plug filters and fine orifices or cause deposit layers on hot surfaces. (Extensive work has established that the breakdown is the result of the oxidation of trace constituents and not a breakdown of the basic hydrocarbon structure which takes place at higher temperatures.) Military engines generally place a higher thermal stress on the fuel than do civil engines. Thermal stability has become increasingly critical in the design of the thermal management systems of advanced high performance military engines. Starting in 1989 the U.S. Air Force initiated a broad program to develop a thermal stability improver to reduce fuel system fouling in current military engines and provide the additional heat sink needed by future engines. The additive package developed is referred to generically as +100 because it increases the bulk fuel design limit at the fuel nozzle by 100°F from 325° to 425°F. The U.S. Air Force fuel containing the additive is called JP-8+100, also designated as NATO F-37. Laboratory tests and flight experience have shown that the +100 additive dramatically reduces deposits that cause fuel system fouling. The approved additive package for military engines as of this writing is GE Betz SpecAid 8Q462, consisting of an antioxidant, metal deactivator, and a detergent/dispersant. AeroShell Performance Additive 101 has the same composition and is also approved. At present, the additive is listed in the JP-8 specification. The normal additive treating rate is 256 mg/L. More details on the additive are given earlier in the section on JP-8 fuel.

1.2 DESCRIPTIONS OF TEST METHODS

This section contains brief descriptions of the standard test methods contained in the preceding commercial and military specifications. Most of the methods are ASTM standards, a few are contained in U.S. military specifications. British methods by the Institute of Petroleum are shown only if they differ significantly from U.S. methods. Russian test methods are not included.

1.2.1 Acidity by D 3242

The fuel sample is dissolved in a mixture of toluene and isopropyl alcohol containing a small amount of water. The resulting single phase solution is blanketed by a stream of nitrogen bubbling through it and is titrated with alcoholic potassium hydroxide to an end point indicated by the color change of p-naphtholbenzene. Results are reported in mg KOH/100 g.

1.2.2 Aromatic Content by D 1319

Fuel is percolated through a column of silica gel containing special fluorescent dyes. When desorbed by alcohol, the fuel separates into three layers of hydrocarbon types which become visible under ultraviolet light. The hydrocarbon groups are olefins, aromatics and saturates (paraffins and naphthenes). The relative length of each band is translated into the volume percent of each hydrocarbon type.

1.2.3 Clear and Bright Appearance Test by D 4176

A sample is placed into a 1 liter glass container and is swirled. The bottom of the container is inspected visually for particles or water droplets. Under Procedure 1, the fuel is examined for visual haze and is rated as clear or hazy. Under Procedure 2, a standard bar chart is placed behind the container and the rater compares the appearance of the bar chart with a set of standard photos. The sample is given the rating number of the photo most closely resembling the sample.

1.2.4 Color of Dyed Aviation Gasolines by D 2392

For minimum required dye level, a sample of dyed avgas is placed into a special comparator in which the hue (color) and intensity are compared to colored glass standards. The hue has to match the standard. The intensity has to be between the minimum and maximum allowed. Results are reported as *pass*. (Maximum color levels can also be affected by the permitted maximum dye concentration. The actual dye concentration is also reported.)

1.2.5 Color by Saybolt Chromometer by D 156

Fuel is placed into a sample tube and its color is observed by looking through the length of the sample tube and comparing the color to the standard in an adjacent tube. (Both tubes are visible in the eye piece.) The sample height is decreased until the sample color matches the color of the standard in the other tube. The reported fuel color is

based on the final height of the fuel column and the particular standard used. Results are reported as values ranging from +30 (water white) to -16 (straw color).

1.2.6 Color by Automatic Tristimulus Method by D 6045

The fuel sample is poured into the glass sample container which is placed into the light path of the automatic instrument. A transmittance measurement determines the Tristimulus values of the sample. For aviation fuel samples these values are converted by the instrument to Saybolt color by the appropriate algorithm in the instrument. Results are reported as values ranging from +30 (water white) to -16 (straw color).

1.2.7 Corrosivity of Copper by D 130

A polished strip of copper is immersed into 30 mL of test fuel and placed into a pressure vessel where it is heated for 2 hours at 100°C. After washing, the strip appearance is compared to the ASTM copper strip corrosion standard for rating. Corrosion ratings range from 1 (no significant corrosion) to 4 (corrosion) with each numbered category having two or more lettered subdivisions.

1.2.8 Density by Hydrometer by D 1298

A hydrometer is floated in fuel in a cylinder or graduate and is spun to avoid wall contact. After the hydrometer comes to rest, fuel density is read on the scale in the hydrometer at the top of the fuel level. Simultaneously the fuel temperature is measured with a thermometer. Both density and temperature are reported. If desired, the density can be corrected to a standard temperature. Results are reported in kg/m³.

1.2.9 Density by Digital Density Meter by D 4052

A small volume of liquid sample is introduced into an oscillating sample tube. The oscillating frequency is established using water or other calibrating liquid. The change in oscillating frequency caused by the change in the mass of the tube when testing the sample is compared to the calibration data to determine the density of the sample. Results are reported in kg/m³.

1.2.10 Distillation of Petroleum Products by D 86

Fuel is heated at a constant rate in a flask and the vapors are boiled off. The vapors are condensed and collected. The distillation curve is the relationship between the percent of condensed vapor and the vapor temperature. Results are reported in °C per percent recovered.

1.2.11 Distillation (Simulated) by D 2887

Fuel is passed through a chromatographic column which separates hydrocarbons in boiling point order. Boiling temperatures are assigned from a calibration curve, obtained by running a known mixture of hydrocarbons under the same conditions. From these data a boiling point distribution is obtained. Results are reported in °C at per percent recovered.

1.2.12 Electrical Conductivity by D 2624

A probe is immersed into the fuel sample and the conductivity is read directly on the conductivity meter. Depending on the manufacturer the probe may be attached to the meter or be at the end of a flexible cable. Conductivity is reported in pS/m. Sample temperature is also measured and reported.

1.2.13 Flash Point by D 56 or D 93

A sample is heated at a prescribed rate in closed container. Periodically the container is opened slightly and a small flame is introduced to try to ignite the vapors. The flash point is the temperature at which vapors ignite and then go out. Flash points are reported as °C.

1.2.14 Filtration Time Test by Appendix A of MIL-DTL-83133

In the laboratory one gallon of fuel is pulled through a membrane filter with a pore size of 0.8 micrometers by a vacuum of 50 mm (20 in) Hg minimum. The time required to filter the sample and the weight gain of the membrane are recorded.

1.2.15 Freezing Point (Manual Method) by D 2386

The sample is placed into a test tube which is in a vacuum flask containing a mixture of dry ice and isopropyl alcohol. The tube contains a thermometer and a stirring rod immersed in the sample. The fuel is cooled at prescribed rate until wax crystals appear. (Water/ice crystals are ignored.) The fuel is then warmed until the last crystal melts. The freezing point is the temperature at which the last crystal melts.

1.2.16 Freezing Point (Phase Change Method) by D 5972

A 150 μ L sample is placed into apparatus with micropipette. A built-in cooler controls the sample cooling rate. Crystal appearance and disappearance is monitored by 130 light detectors focused on a concave, shallow lens. The test sequence is automatic and the freezing point is read directly on the instrument in $^{\circ}$ C.

1.2.17 Fuel System Icing Inhibitor by D 5006

The FSII in a measured volume of fuel is extracted with a fixed ratio of water. A few drops of the water extract are placed on the prism of a refractometer. In one refractometer, FSII content is read directly in volume percent. In a different refractometer a temperature correction is followed by minor calculations to obtain FSII content in volume percent.

1.2.18 Gum Content (Existent) by D 381

A weighed quantity of fuel is evaporated at 232 $^{\circ}$ C (450 $^{\circ}$ F) by blowing with superheated steam. After evaporation the residue is weighed and reported as existent gum. Solvent washing of the gum, as is done for motor gasoline, is not permitted. Gum content is reported as mg/100 mL.

1.2.19 Gum Content (Potential) by D 873

Avgas and pure oxygen are heated in a pressure vessel at 100 $^{\circ}$ C for 5 or 16 hours. The existent gum content is obtained on the oxidized fuel by D 381. Any precipitate formed during the test is also weighed. The sum of the two weights is called potential gum and is reported in mg/100 mL.

1.2.20 Hydrogen Content by D 3701

A sample of fuel is compared with a pure hydrocarbon standard (dodecane) in a low resolution nuclear magnetic resonance spectrophotometer. Based on this comparison the instrument calculates and indicates the hydrogen content in mass percent.

1.2.21 Hydrogen Content by D 3343

Hydrogen content is calculated by using an equation relating hydrogen content with distillation range, density and aromatic content. Hydrogen content is reported as percent by mass.

1.2.22 Lead Content by D 3341 or D 5059

Lead content is measured by X-ray spectroscopy, as well as by wet chemical extraction followed by titration. Lead content is reported as mL TEL/L or g Pb/L.

1.2.23 Lubricity by D 5001

In the Ball-on-Cylinder Lubricity Evaluator (BOCLE) test a fixed steel ball, under load, is pressed against a rotating cylinder, covered by fuel, for a predetermined period of time. Both the temperature and humidity of the air around the test section are controlled during the test. Fuel lubricity is based on the size of the resulting elliptical wear scar on the ball. The reported wear scar size, in millimeters, is the major axis plus the minor axis divided by two. Wear scar is reported in mm. Fuels giving high wear scars have poor *lubricity* or have been called *hard* fuels.

1.2.24 Mercaptan Sulfur by D 3227

The fuel sample is dissolved in an alcoholic sodium acetate titration solvent and titrated potentiometrically with silver nitrate solution. Mercaptan sulfur content is reported in mass percent. (A permitted alternative can be the Doctor Test, D 4952, in which the sample is shaken with sodium plumbite solution to which a small amount of powdered sulfur is added. The presence mercaptans or hydrogen sulfide will result in discoloration of the sulfur at the interface or discoloration of either liquid phase. Results are reported as pass or fail.)

1.2.25 Naphthalenes Content by D 1840

The naphthalenes content (double ring aromatics) is determined by ultraviolet absorption at a wave length of 285 nm. Naphthalenes concentration is established by using the average response of a standard blend of naphthalenes. Naphthalenes content is reported in mass percent. (Usually performed in conjunction with smoke point.)

1.2.26 Net Specific Energy or Net Heat Content by Bomb Calorimeter by D 4809

A weighed quantity of fuel is burned in a closed pressure vessel, itself immersed in a water bath. The total heat released by the fuel is calculated from a very accurate measurement of the temperature rise of the water. Net specific energy is calculated by correcting for the condensation of water and sulfur reaction products. Net specific energy is reported in MJ/kg or BTU/lb. (The net specific energy can also be calculated by measuring other properties which have been shown to correlate with heat content. These properties include density, aniline point, boiling point, and aromatic content in D3338, or aniline point and density of D 4529.)

1.2.27 Aviation Gasoline Lean Rating by D 2700

The compression ratio in a standard single cylinder laboratory engine is raised until knock is detected by an electronic knock sensor. The knock level is rated by testing a series of blends with varying ratios of iso-octane to normal heptane until one blend knocks under the same conditions as the test sample. The percent of iso-octane in the matching blend is the motor octane number of the sample. A table in the method is used to convert motor octanes to aviation octanes. Aviation gasoline lean ratings are expressed as octane numbers up to 100 and performance numbers above 100.

1.2.28 Aviation Gasoline Rich Rating by D 909

Using a supercharged single cylinder laboratory engine, the fuel flow and manifold pressure are varied to develop a curve of knock-limited fuel/air ratio against indicated mean effective pressure (IMEP). This curve is bracketed by two curves, each obtained on iso-octane containing differing levels of TEL (reference blends). The power output of the test fuel is obtained by interpolation between two lead/iso-octane blends at maximum power. The performance number is the approximate percent power increase relative to iso-octane.

1.2.29 Particulates by Field Filtration by D 2276

A fixed volume of fuel (usually 5 L or 1 gal) is forced, under line pressure, through a membrane having a pore size of 0.8μ . After drying the membrane, its color is rated by comparing it to a color standard. In a different version of the procedure the weight gain of the membrane, after field filtration, is determined in a laboratory. The weighing procedure is the same as in D 5452, Particulates by Laboratory Filtration.

1.2.30 Particulates by Laboratory Filtration by D 5452

A known volume, usually 4 L, is filtered through two preweighed, matched weight membranes in series, having a pore size of 0.8μ , using a vacuum downstream of the membranes. The increase in weight of the upper membrane is determined after washing and drying of the membrane. Any change in weight of the second or control membrane is also determined. The particulate contaminant level is the difference in weight gain of the two membranes. Results are reported in mg/L or mg/gallon. The method can also be used to conduct the Time Filtration test.

1.2.31 Smoke Point by D 1322

Fuel is placed into a wick-fed kerosine lamp and the wick is ignited. A scale marked in millimeters is behind the flame. The wick is raised until the tip of the flame starts to smoke. The wick is then lowered until smoke disappears. The smoke point is the maximum height of the flame at which no smoke is noted. Smoke point is reported in mm.

1.2.32 Sulfur Content

A variety of methods are available for the quantitative determination of sulfur content. These include combustion methods in which the resultant sulfur oxides are measured, as well as measurement of the X-ray fluorescence of the sulfur compounds or measurement of the fluorescence of sulfur oxides exposed to ultraviolet radiation. Sulfur content is reported in mass percent.

1.2.33 Undissolved Water Content of Aviation Fuel by D 3240

The 500 mL of fuel is filtered under line pressure through a dye-treated membrane. Any undissolved or free water reacts with the dye causing it to fluoresce under ultraviolet light. Relative fluorescence is measured in the Aqua-Glo instrument by comparing the filter pad to an internal standard. Free water content is read directly on the instrument in parts per million of free water.

1.2.34 Thermal Stability by Jet Fuel Thermal Oxidation Tester (JFTOT) by D 3241

1.2.34.1 Nitrogen Pressure System

The 450 mL of fuel is placed into a closed system that is pressurized by nitrogen to 500 psi (3,500 kPa). The fuel flows over a heated aluminum tube into a filter screen, through a cooler and then a metering pump which regulates the flow rate. The maximum tube temperature is the test control variable. The fuel makes one pass through the system. A fuel's oxidation resistance is measured by the color and extent of deposits on the tube and the pressure drop across the filter at the end of the test. Color ratings range from 0 to 4, with 0 being a clean tube, while 4 represents dark deposits. Pressure drop is reported in mm of Hg.

1.2.34.2 Hydraulic System

In this later version of the method fuel is pushed through the system by a hydraulic piston driven by a screw. The test section, operating conditions and the evaluation of test results are identical to the nitrogen pressure system.

1.2.35 Vapor Pressure (Reid) by D 323 or D 5191

The Reid vapor pressure is the pressure exerted by a fuel when heated to 38°C in a pressure vessel with a vapor-to-liquid ratio of 4:1. Prior to the test the sample is saturated with water. Reid Vapor Pressure includes the partial pressures of air and water vapor. Vapor pressure is reported in kPa or psi.

1.2.36 Viscosity by D 445

A fixed volume of fuel flows through capillaries of specific diameters and lengths at standard temperatures. The viscosity or resistance to flow is calculated from the flow time and the capillary constant. Viscosity is reported in mm²/s or cSt.

1.2.37 Water Reaction by D 1094

Twenty mL of buffered water is added to 80 mL of test fuel in a graduated glass cylinder and is shaken by hand. After 5 minutes of settling any volume change of either the fuel or the water is reported. For jet fuel the appearance of the interface between fuel and water is rated by comparison to a series of written descriptions which are numbered 1 through 4, with 1 being the cleanest interface.

1.2.38 Water Separation Characteristics by Portable Separometer by D 3948

A fuel/water emulsion is created in a disposable syringe with a high speed mixer. The emulsion is then pushed through a special fiber glass filter intended to strip the water from the emulsion. The presence of water in the filtrate is then determined by exposing the filtrate to a light beam and measuring the resultant light scatter due to water droplets. Results are given in MSEP units, with a fuel having an MSEP rating of 100 showing no light dispersion due to free water, while a rating of 0 indicates a filtered fuel heavily contaminated with free water.

1.3 COMPOSITION OF FUELS

In general, the composition of aviation gasoline and turbine fuels tend to be based on the fuel's properties and performance rather than a specified, detailed chemical composition. While aviation gasolines (with the exception of ASTM D 6227 Grade 82 UL) are generally composed of a limited number of hydrocarbons, turbine fuels can contain hundreds of different hydrocarbons. They are, therefore, defined by general property limits. This category of turbine fuels includes Jet A, Jet A-1, Jet B, JP-4, JP-5, JP-7, JP-8, RP-1, and JP-TS. The active missile fuels RJ-4 and JP-10 are, on the other hand, essentially pure or mixtures of a few pure synthesized hydrocarbon compounds tailored to their operational use, with high density as a primary requirement.

1.3.1 Major Fuel Constituents

Although made up of many different hydrocarbon molecules, fuels consist basically of three groups of compounds, paraffins, naphthenes or cycloparaffins, and aromatics. The proportion of each will vary with the types of crude oils from which the final fuel is derived and the refining processes used. Olefins are generally present only in trace amounts.

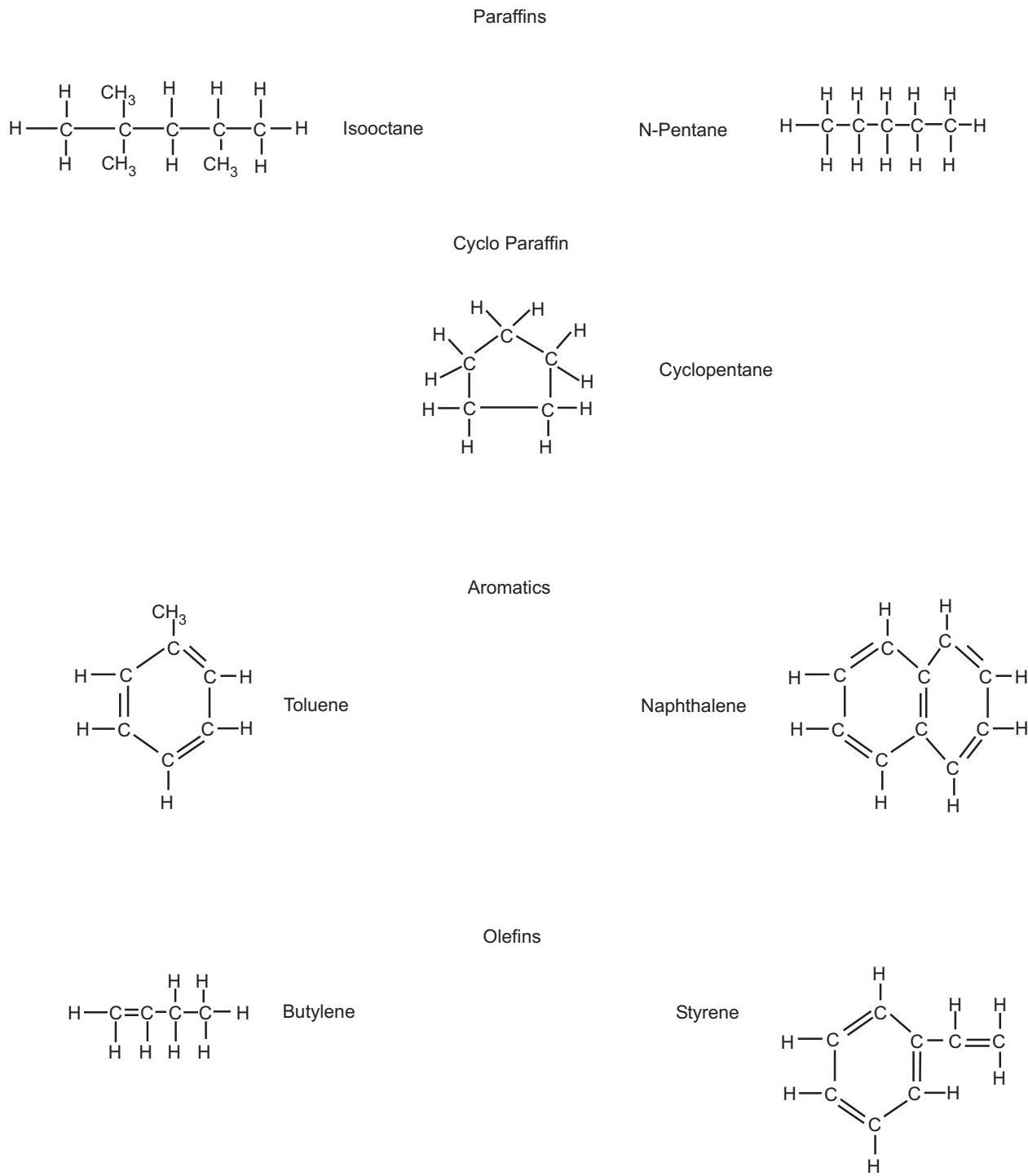
Paraffins are one of the major components of aviation fuels. Paraffins consist of single bonded carbon chains in which each carbon atom is fully saturated with hydrogen. They may be straight chain ("normal") or branched chain (iso-paraffin) molecules. This makes for a very stable structure, not readily reacting with materials with which they come into contact, such as elastomers, paints and various metals. The high hydrogen-to-carbon ratio gives them high heat release per unit weight, and makes them cleaner burning than other hydrocarbons.

The structure of paraffin molecules has a major effect on gasoline knock resistance. Normal paraffins have poor knock resistance, while isoparaffins have high knock resistance. The C8 isoparaffin, iso-octane, is the major constituent of high octane aviation gasoline with other paraffin types eliminated as much as possible. The structure of both compounds is shown in **Figure 1-1**. Turbine fuels on the other hand can contain significant levels of normal paraffins, typically ranging from 8 to 16 carbon atoms per molecule. These paraffins have relatively high melting points and the paraffins with high carbon numbers have a major adverse effect on the fuel's freezing point.

Naphthenes or Cycloparaffins – Naphthenes have a saturated ring structure that decreases the hydrogen-to-carbon ratio and lowers the heat release per unit weight, but increases their density. Naphthenes are very stable and clean burning. Their primary advantage is that, in general, their freezing points are lower than comparable normal paraffins with the same number of carbon atoms. An example is shown in **Figure 1-1**. Because of their lower knock ratings naphthenes are not usually found in aviation gasolines.

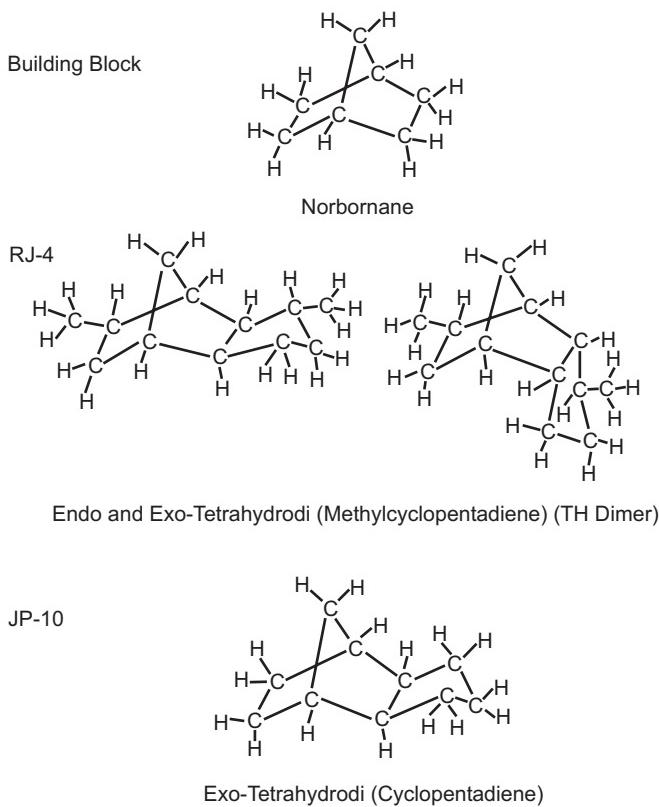
Aromatics – Aromatics are unsaturated, cyclic hydrocarbons containing one or more carbon rings, each with six carbon atoms. The six-carbon member ring structure may be substituted with paraffin or olefin structures and/or may be coupled to form polynuclear aromatics. Being hydrogen deficient they have, in general, higher heat content per unit volume, but a lower heat content per unit weight compared to paraffins with the same carbon number. They tend to cause swelling in rubber and certain sealants. They can also extract the plasticizer in elastomers.

Aromatics in aviation gasoline are mostly toluene or xylene. Both have high knock resistance and are used as blending stocks to increase gasoline octanes. The lowest boiling aromatic, benzene, is not used in aviation gasoline because of its unusually high freezing point. Although not specifically limited the aromatic content of aviation gasoline tends to be below 25 percent to meet the minimum specific energy requirements of the specification.



136636.cdr

Figure 1-1. Examples of Hydrocarbon Compound Types



136637.cdr

Figure 1-2. Chemistry of High Density Hydrocarbon Missile Fuels

In turbine fuels, aromatics tend to form smoke when burned, tend to form coke deposits on combustor surfaces, and contribute to high-luminosity flames. Due to these factors, the maximum concentration of aromatics is controlled in the various specifications with maximums in the range of 20 to 25 percent by volume. Double ring aromatics or naphthalenes are separately limited at 3.0 percent because of their adverse effect on combustion. The aromatic content of turbine fuels varies with crude source and processing with typical values in the range of 10 to over 20 percent. The aromatic content of synthetic fuels manufactured by processes such a Fisher-Tropsch can be very low. Blending with fuels of higher aromatic content may be necessary to minimize seal leaks.

Olefins – Olefins are similar to paraffins, but are unsaturated (have one or more double bonds between carbon atoms), and therefore, have lower hydrogen-to-carbon ratios. They are more reactive than other hydrocarbons due to the nonconjugated double bonds. They are found in very low concentrations in kerosine distilled from petroleum, but tend to be formed in larger quantities as the result of certain refinery cracking processes. Both the high temperature stability and storage stability of turbine fuels are adversely affected by high olefin content. For that reason unhydrotreated cracked stocks are not used in jet fuel or aviation gasoline, so that olefin content is usually very low.

1.3.2 Other Fuel Constituents

Hetero-Organic Compounds – Hydrocarbon compounds containing other elements such as sulfur, oxygen, and nitrogen are termed hetero-organic compounds or hetero-atoms. Such molecules originate in the crude oil and are present in straight-run turbine fuels. Although often present in concentrations on the order of a few parts per million, they can act as lubricity improvers or oxidation inhibitors but may contribute to deposit formation and degraded water separability.

Sulfur and Sulfur Compounds – All known crude oils contain sulfur in varying concentrations. Sulfur is usually in the combined form as mercaptans, sulfides, disulfides, thiophenes, and other sulfur-containing compounds. Infrequently, sulfur may exist in the free (elemental) form, when it can be corrosive to certain metals in the fuel system. Free sulfur is controlled by measuring its corrosive effect on copper. Hydrogen sulfide, usually the result of faulty processing, has a similar corrosive effect and is controlled in the same fashion. Mercaptans attack cadmium plating and can cause deterioration of some types of synthetic rubbers. Mercaptan sulfur content is limited by the specifications. The total of combined sulfur compounds are controlled by the total sulfur content limits found in various specifications.

Naphthenic Acid – Naphthenic acids are organic acids that originate in the crude oil. Part of their boiling range is similar to kerosine. Therefore, these acids may be present in aviation turbine fuels. They can cause corrosion of aluminum and magnesium if water is present. Zinc is rapidly attacked by these acids, forming zinc naphthenates that are soluble in the fuel. Naphthenic acids will form soaps or surface-active materials when they react with metals. Although there is no direct specification limiting the naphthenic acid content, the total acidity limit controls this constituent. Refining techniques such as caustic washing or hydrotreating in conjunction with clay filters can remove naphthenic acids and eliminate potential problems.

1.4 HISTORICAL EVOLUTION OF SPECIFIC FUELS

1.4.1 History of Aviation Gasoline

Until World War I (WW I) automobiles and aircraft used the same fuel: straight-run gasoline. The first specification for a motor gasoline was published by the U.S. Navy in 1907, designated U.S. Navy Specification 24G5. The first cracking process was patented in 1913, allowing refineries to increase their gasoline yields. It was discovered that a cracked fuel, being high in olefins, had good anti-knock properties. However, such gasoline caused deposit problems and the use of cracked fractions in aviation gasoline was, therefore, prohibited. Later, the introduction of antioxidants would address this instability, and the ban on cracked fractions would be relaxed.

There was no separate specification for aviation gasoline until after World War I. Before then, aviators had used *high test* fuel as opposed to *civil*. This high-test gasoline was more volatile than the civil grade, having a lower final boiling point and a lower density. In the U.S., high test probably had an octane rating of 45 to 55 due to the paraffinic crude oil from which it was made. During the same time period, fuel in Europe was being made from aromatic East Indies or Borneo crudes. Because of the crude oil differences, these fuels are believed to have been closer to a 70 octane rating. During WW I, the U.S. provided gasoline referred to as Grade X to the European theater. Because of the difference in octane number, the French engines, developed with the 70 octane number fuel, would operate on the U.S. fuel, but were quickly damaged by overheating.

In June 1918, the first aviation gasoline specification was written by the U.S. military. This aviation gasoline was highly volatile with a low distillation end point and contained no real performance parameters. Knock, carburetor icing, and vapor lock had not been recognized as problems. In 1923, the first British specification for aviation covered Aviation Spirit, Grade 720 and 760, where the numbers referred to the specific gravity of the fuel. Engine studies performed by the Royal Aircraft Establishment during this period showed a relationship between detonation and engine overheating. Cylinder head temperatures were high, particularly when fuel/air ratios were decreased to near stoichiometric to reduce fuel consumption. Detonation, the uncontrolled sudden burning of the fuel, caused the overheating of spark plugs, valves, pistons and cylinder heads. By increasing the fuel/air ratio (operating at a *richer* mixture) or by adding benzene the engines ran cooler, thereby reducing pre-ignition or detonation.

In the 1920's, laboratory engine tests were developed to measure the knocking tendency of fuel. In these test procedures a fuel's detonation characteristics were compared with those of a mixture of two reference fuels. The two fuels were n-heptane, defined as zero octane due to its severe detonation characteristics, and iso-octane, defined as 100 octane because of its resistance to detonation. By mixing the reference fuels together in different volumetric proportions, intermediate detonation characteristics could be simulated. When the blend of reference

fuels matched that of the test fuel, the percentage of isoctane in the matching blend became the *octane number* of the test fuel. The higher the number, the more the fuel resisted detonation.

In one of the most significant discoveries involving gasoline performance, the anti-knock properties of tetraethyl lead (TEL) were discovered in 1921. Unfortunately, when TEL was added to the fuel, the resultant lead oxide quickly plated out on engine surfaces, precluding its use. Not until the advent of lead scavenger additives did the use of TEL become practical.

The U.S. Navy first successfully used tetraethyl lead in 1927 with the inclusion of ethylene dibromide as the lead scavenger. In 1930, the U.S. Army Air Corp specified a minimum of 87 octane number. With U.S. fuels, the only way to meet this requirement was with TEL. The maximum TEL level was set at 3 cc/gallon. To distinguish the lead-treated aviation gasoline from other gasolines, the fuel was dyed blue. The dye presence thus identified the fuel as containing some level of TEL. By 1935, the U.S. Navy's specification had four different octane grades, 73, 80, 83, and 87. Because of differences in test method, the 87 octane number grade U.S. Navy fuel was the same as the U.S. Army's 92 octane number fuel.

With TEL and newly developed base stocks, it became possible to achieve a 100 octane or higher grade fuel. Originally detonation occurred primarily when mixture ratios were leaned out in flight for better engine efficiency. That tendency was measured by the aviation knock test or *lean* method and is the basis for the first octane number of two ratings. As engine output was increased through supercharging and other techniques, detonation also occurred under takeoff or rich fuel/air ratios. That finding led to the development of the "rich rating" method which has become the second rating for aviation gasolines. Rather than try to define an artificial octane over 100, a scale of aviation performance numbers was developed which showed the percent improvement of increased knock-limited engine output over unleaded isoctane.

In 1942, the U.S. Army Air Corp specification AN-F-28 included a lean rating of 100 and a supercharged rich mixture knock rating of 130, the product being designated as Grade 100/130. In 1944, the U.S. military specification AN-F-33 was issued for an aviation gasoline grade of 115/145 for use in high output engines. To achieve such high ratings, it was necessary to use 4.6 cc TEL/gallon as well as greater concentrations of high octane base stocks. For such engines in somewhat less demanding civil applications, a 108/135 grade was introduced. This fuel used the same base stock as the 115/145 grade, but limited the maximum TEL content to 3.0 cc/gallon.

Before 1939, there was little coordination between the engine manufacturers, so each company had its own requirements and specifications for fuel. World War II, by necessity, brought about some standardization. Still, in 1945 and 1946 there were over a dozen grades of gasoline due to the rapid engine development that was occurring. In 1945, ASTM issued D 615 which was then replaced by the current D 910. That specification contained four grades of gasoline: 80/87 (red) with 0.5 cc TEL/gallon, 91/96 (blue) with 4.6 cc TEL/gallon, 100/130 (green) with 4.0 cc TEL/gallon, and 115/145 (purple) with 4.6 cc TEL/gallon.

This picture changed radically with the advent of turbine engines in airline service. As airlines switched to jet fuel, gasoline volumes decreased drastically and first the 91/96 and then the 115/145 grade disappeared. By then the remaining aviation gasoline was consumed in general aviation service. Most general aviation dealers had two fuel systems, one for 80/87, the other for 100/130. To add jet fuel to their inventory without having to build another fuel system, it became necessary to find a single grade of gasoline that would satisfy both low and high output engines. This led to the development of the blue 100LL grade that, with a reduced TEL content of 2 mL/gallon, was designed to satisfy both requirements. Today, virtually all aviation gasoline in the U.S. and much of the rest of the world is the 100LL grade. Elsewhere it is the higher TEL, 100 grade gasoline. There is relatively little 80/87 gasoline in current use. The 91 grade has been added recently for engines certified for that grade.

1.4.2 History of Turbine Fuels

Military Turbine Fuel Development – Beginning in the late 1930's, both Great Britain and Germany initiated research on turbine aircraft engines. Illuminating kerosine was chosen as the fuel for the British turbine engines, while the German fuel was a blend of kerosine and unleaded gasoline. The British fuel specification was designated RDE/F/KER Provisional and in 1947, became known as D.Eng.RD 2482, or more commonly, DERD 2482. To accommodate long range, high altitude flights, a lower freezing point fuel specification, DERD 2494, ultimately replaced DERD 2482.

JP-1 – In the U.S., the first military turbine fuel was designated as JP-1. It had the same freezing point as aviation gasoline and its other properties matched those of the British fuel. JP-1 had a minimum flashpoint of 105°F and a distillation endpoint of 600°F. The low freezing point and high flashpoint severely limited the availability of the fuel. Only 1 percent of crude could be separated as JP-1. This fuel grade was covered by U.S. Air Force specification AN-F-32a released in 1944. In 1950, the specification designation was changed to the coordinated MIL-F-5616.

JP-2 – In order to increase the availability of fuel, a wide-cut distillate was considered. Called JP-2, per AN-F-34, it was only experimental due to viscosity and flammability issues.

JP-3 – A more successful wide-cut fuel designed to support large missions of 1,000 or more aircraft, JP-3 had the same vapor pressure limits as aviation gasoline. It was essentially a blend of kerosine and naphtha (straight-run gasoline) and was intended to yield as much as 25 percent of the fuel from crude oils. JP-3 was first specified as AN-F-58 in December 1947. In March 1949, the specification was upgraded to AN-F-58A and then to MIL-F-5624. However, JP-3 caused unacceptable fuel losses due to boiling during rapid climb in the high performance Century series of fighters. It also caused vapor lock problems.

JP-4 – To solve the boil-off problem, JP-3 vapor pressure was reduced to 2.0 to 3.0 lb/in² and the product was called JP-4. The lower vapor pressure made JP-4 a somewhat less available fuel than JP-3. JP-4 was added to MIL-T-5624 in May 1951. JP-4 was composed of 50 to 60 percent naphtha and 40 to 50 percent kerosine. In May 1955, revision C clarified JP-4 as a low vapor, wide-cut gasoline. The specification also allowed the limited use of cracked stocks as controlled by a maximum bromine number. When the use of the cracked stocks caused thermal stability problems, a maximum olefin content of 5 percent by volume was added and the bromine number was dropped. Today, JP-4 has been replaced by JP-8.

JP-5 – This fuel was developed for the U.S. Navy as a blending stock to extend aviation gasoline supplies aboard ship. Referred to as *jet mix*, it was never used operationally because the lead in aviation gasoline attacked the hot sections of turbine engines. Eventually, the blending stock became JP-5. The primary change from regular kerosine was an increased flash point, calculated to minimize fuel vapors in carrier tankage ullage spaces under combat conditions. In 1953, JP-5 appeared in the military specification, MIL-F-5624. Subsequent nomenclature changes in the specification finally resulted in the current version, MIL-DTL-5624, in September 1998.

JP-6 – This fuel was a kerosine fuel developed in 1956 for the XB-70. It had a lower freezing point and increased thermal stability over JP-5. Work on the fuel and the specification was cancelled when the XB-70 program was cancelled in 1967.

JP-TS – Jet Propulsion Thermally Stable was developed for the U-2. It has a low freezing point and high thermal stability. Because of the secrecy around the U-2 program, JP-TS did not become widely known until after 1970. Originally the program used commercially available lighter fluid, called LF-1. A fuel with the same characteristics is now covered by the military specification, MIL-DTL-25524.

JP-7 – This fuel was a highly hydroprocessed fuel specifically developed for the supersonic YF-12 and SR-71. The fuel consisted essentially of naphthenes and paraffins, with a very low vapor pressure and very high thermal stability. It had a high net heat of combustion, a low aromatics content of less than 3 percent by volume, and a freezing point of -43.5°C. Its military specification, MIL-DTL-38219, was not released until 1970.

JP-8 – In 1967, the Tactical Air Command requested a fuel which was less susceptible than JP-4 to aircraft fires caused by ground small arms fire and low velocity crashes. The limited availability of JP-5 precluded its being used across the services, so a new fuel had to be developed.

Requirements for the new fuel defined it to be a hydrocarbon fuel with the necessary availability, reasonable cost, and suitable physical and chemical properties to permit substitution for JP-4 without extensive modifications or serious degradation of aircraft performance. Jet A and Jet A-1 were already the civil standards. Jet A-1, which had a -50°C freezing point and worldwide availability, was a logical start. After extensive studies the U.S. Air Force adopted Jet A-1 as the new base fuel, added anti-icing, static dissipator additive (SDA), and corrosion inhibitor additives and designated the resulting fuel as JP-8. Released in 1976 as MIL-T-83133, JP-8 became the U.S. Air Force's fuel of choice in the early 1980s. The specification has been reissued as MIL-DTL-83133.

The conversion to JP-8 was not without incident. It was found that some aircraft fuel systems that had previously been fueled with JP-4 and then were fueled with JP-8 would leak badly. If all packings and seals were replaced before fueling with JP-8, no leaking was observed. Apparently a difference in the chemical composition of the fuels caused the elastomers to react differently to JP-4 than to JP-8. The O-rings and seals would swell and take a set during a lifetime in JP-4. When then contacted with JP-8, the packings would shrink slightly and the seals that had taken a set (compressed to a smaller size, usually in the shape of the gland) would leak. Replacing the seals solved the leak problems.

Two other concerns dealt with the ability to start engines at extreme cold temperatures and to re-light them at altitude. At higher altitudes, there were increases in the time required for restarts and for some engines, the maximum altitude for restarting decreased. The ground cold start issues were addressed using hangars, hot air ground carts, and other methods of heating the engine. In some locations where ground starting was a problem for certain engines, it was possible to substitute aircraft with different engines. In the case of B-52 aircraft with TF-33 engines, cold engines are started with JP-4 and then switched to JP-8. It was determined that at temperatures where JP-8 would not reliably ignite, the other fluids in the engine were also cold soaked to the point that starting the engine became difficult. When the civil aviation industry increased the minimum freezing point of Jet A-1 from -50°C to -47°C, the U.S. Air Force had to repeat much of their earlier testing and then also raised the minimum freezing point of JP-8 to -47°C.

By 1998, JP-4 was no longer being widely produced, making JP-5, JP-8, and JP-8+100 the only routine aviation turbine fuels available. JP-7 and JP-TS continued to be available for specialized applications.

High Temperature Stability Improver Development – Effort in the early 1960's resulted in the development of a thermal stability improver called Jet Fuel Additive No. 5 (JFA-5) manufactured by Dupont. JFA-5 was never broadly used but is required in MIL-DTL-25524E, JP-TS fuel to help ensure good thermal stability. The primary thermal stability enhancement of JP-TS over that of conventional JP-8 is the result of special refinery processing of the fuel. JFA-5 by itself was not expected to provide a large improvement in fuel thermal stability.

Recognizing the need for a high-temperature fuel improver, the U.S. Air Force started an extensive research program in the 1980's to develop such an additive. As stated in the earlier Additive section, such an additive is identified as JP-8+100 and is approved as a proprietary material. The search for additional formulations is continuing and candidate additives from a number of manufacturers for use are being evaluated as a thermal stability improver in the JP-8+100 formulation at the time of this writing.

A major drawback to JP-8+100 was identified early in its development. The dispersant/detergent component of the +100 additive package is a strong surfactant and rapidly disarmed the coalescer elements in filter separators. Such filter separators are used in bulk-fuel storage facilities and air bases to remove free water and dirt. Fuel monitors which are blocked by the presence of water are not affected by the additive. The U.S. Air Force temporarily resolved the problem by using monitors as the final filter just ahead of the aircraft and injecting the additive ahead of the monitor but downstream of any filter separator so that the filter separators never see the additive. In addition, the U.S. Air Force-funded programs with the major filter separator manufacturers to develop

filter separators compatible with JP-8+100. A number of filter manufacturers now have JP-8+100 compatible filter separators commercially available. Another logistical problem is defueling an aircraft for maintenance. JP-8+100 fuel off-loaded from an aircraft cannot be returned to an airport or airbase bulk fuel storage tank containing straight JP-8 unless the fuel system is outfitted with the +100 compatible filter separators. Currently, the JP-8+100 fuel must be transferred to another aircraft using JP-8+100, transferred to a dedicated storage tank, or diluted 100 to one with fuel not containing the additive.

1.4.3 History of Missile Fuels

Ramjet Fuels – Following after RJ-4, which is still active, RJ-5 was originally specified by the U.S. Air Force and flight-tested on the ASALM. RJ-5 was replaced by RJ-6 due to RJ-5’s unsatisfactory low temperature properties. RJ-6 was intended for the U.S. Navy/Air Force Long Range Conventional Standoff Weapon (LRCSW). Neither RJ-5 or RJ-6 is currently active.

Missile Turbine Fuels – Fuel storage volume in turbine-powered missiles generally is very limited and it is often necessary to develop a fuel with high volumetric specific energy to successfully achieve the missile’s mission. This is particularly true of long range missiles like the Air Launched Cruise Missile (ALCM). For this purpose the U.S. Air Force and Navy first developed *synthetic* (non-distillate) fuel JP-9, a mixture of a small number of high-energy-density hydrocarbons. Due to its high cost and inadequate low temperature properties, JP-9 was eventually replaced by JP-10, a single-component synthetic hydrocarbon illustrated in Figure 1.2.

1.4.4 History of Civil Turbine Fuels

Civil turbine fuel development went a much less circuitous route. The first flight of a turbine-powered airliner occurred in 1948, using a Vickers Viscount with Rolls-Royce Dart engines. It did not enter regular service until 1953. In the interim, a de Havilland Comet with Ghost engines began service for the British Overseas Airways Corporation (BOAC) in 1952. Both aircraft flew on the British kerosine fuel, D.Eng.RD 2482. The progress of civil turbine powered flight slowed dramatically following a series of crashes involving the de Havilland Comet aircraft. Meanwhile, from 1950 through 1958, most U.S. and British air carriers used piston-powered aircraft such as the Douglas DC-6, DC-7, Lockheed Super Constellation, and the Boeing Stratocruiser.

During this period it became accepted that turbine power would eventually replace piston-powered aircraft for long distance flights. The identification of an appropriate fuel centered over safety issues, both in handling and in flight, vapor losses, production availability and cost, and airframe and engine requirements. Studies used commercial kerosine similar to today’s Jet A and JP-4 wide-cut to develop the optimum civil fuel grades. In 1958, the first transatlantic flights took place in a Pan American Boeing 707 with P&W JT-3’s and a BOAC de Havilland Comet 4B with Rolls-Royce Avon engines. Both aircraft used kerosine per DERD 2482. As these aircraft did not have extremely long range, they did not experience the very low temperatures seen on later, longer-range aircraft.

Because of concerns over the formation of wax at low temperatures, especially during long transoceanic flights, a number of programs were initiated to determine actual in-flight fuel temperatures. A study by Boeing found that, at Mach 0.82 cruising speed, fuel tank temperatures dropped to -29°C at the end of the cruise after about 4 hours. At lower speeds the fuel tanks could reach -40°C. In similar studies done by Bristol, it was concluded that a fuel with a freezing point of -50°C would be needed for the new jet transports. This led to the release of DERD 2494 in 1957.

In 1956, Technical Committee J of the American Society for Testing and Materials (ASTM) began writing a U.S. specification using the many individual purchase requirements being established by the airlines. In 1957, the Fuel Study Group of the IATA met to develop guidelines for international civil aviation fuels. These early guidelines ultimately included a Jet A-1 and a Jet B grade. By 1958 ASTM D 1655 included Type A with a -40°C freezing point, Type A-1 with a -50°C freezing point requirement and Type B wide-cut fuel, modeled on JP-4. As late as 1960, refiners were still trying to develop a single fuel for worldwide use, but the heavy jet fuel demand in the U.S. mitigated against Jet A-1 being adopted in the U.S.

With few exceptions, British and U. S. airlines started with and continue to use kerosine-type fuels. In the U.S. Jet A became standardized as the civil turbine fuel; outside the U.S. it was Jet A-1. Canadian airlines used JP-4, in part because of shared fueling facilities with the Canadian Air Force. While there were some safety considerations due to the flammability of Jet B, the primary driver in the U.S. was the Federal gasoline tax levied on Jet B as well as the fuel's lack of availability at most airports throughout the world.

Starting in the 1970s, Jet A-1 suppliers warned of future product shortages if fuel demand continued to increase at high rates. Following studies by airframe manufacturers and international airlines, a higher freezing point of -47°C was agreed upon and introduced into the relevant specifications by the late 1970s.

During this period international fuel suppliers developed the Joint Check List (JCL) to have a common specification which would meet international airline requirements. In turn, the check list was made into IATA Guidance Material by adding ASTM Jet A and Russian TS-1 grades to the JCL.

Although numerous minor changes have since been made in civil specifications, the freezing point increase was the last major change to affect availability. However, fuel specifications have always led a dynamic life and the status quo always seems open to challenges.

1.4.5 Synthetic Fuels

Historically the major Western fuel specifications have assumed that aviation turbine fuels would be derived solely from petroleum crude oils. Beginning in South Africa but now extending to other parts of the world, aviation fuel components are synthesized by the Fischer Tropsch process. Although such fuels are 100 percent hydrocarbons and meet existing specifications, they have raised questions regarding their ability to meet other property requirements which have been assumed but not routinely tested.

A major effort is therefore underway to identify such fuels and assure their *fitness for purpose*. Thus the current Def Stan 91-91 specification has a requirement to encompass and control the use of fuel blends containing components synthesized from non-petroleum sources. Fuels containing synthetic components are approved on an individual basis and are required to meet additional test requirements. Presently blends containing up to 50 percent of South African synthetic fuel are approved for civil use. Ongoing studies hope to extend that approval to 100 percent synthetic fuel. Further details will be found in Def Stan 91-91. However, both the Ministry of Defence and ASTM are working to develop a more general approach for the approval and use of such fuels.

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For U.S. Military Specifications:

Standardization Document Order Desk, 700 Robbins Avenue, Building 4D, Philadelphia, PA 19111-5094

Web site: <http://astimage.daps.dla.mil/online.new/>

For British Defence Standards:

UK Defence Standardization, Kentigern House, 65 Brown Street, Glasgow G28EX, United Kingdom

Web site: www.dstan.mod.uk

For Canadian Specifications:

CGSB Sales Centre, Ottawa, Canada K1A 1G6

Web site: www.pwgsc.gc.ca/cgbs

Handbook of Aviation Fuel Properties

For IATA Guidance Material:

IATA, 800 Place Victoria, PO Box 113, Montreal, Quebec, Canada H4Z 1B1

Web site: www.iata.org

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Technical and Quality Manager, Shell Aviation Limited, Shell Centre, London SE1 7NA, United Kingdom

Web site: www.shell.com/aviation

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2. FUEL PROPERTIES

2.1 FUEL DENSITY

Density is the mass per unit volume relationship of fluids. Generally, relative density is the ratio of the density of a particular liquid fuel to the density of water at 15.5°C and is commonly referred to as specific gravity. These relationships are important in the design of aircraft and missiles, since fuel density variations can have significant impact on determining loaded weight and the range attainable. They are also used in flow calculations, fuel gaging, metering device considerations, fuel loading, thermal expansion of fuels, and fuel tank design.

2.1.1 Density

Density is the mass per unit volume at a given temperature and can be expressed in several mass to volume units. The standard metric practice definition of density is kilogram per cubic meter (kg/m^3). Temperature has a marked and inverse effect on the density of fuels. As the temperature increases, the density of a fuel decreases. *Figure 2-1* shows the effect of temperature on density for major aviation fuels and *Figure 2-2* illustrates the relationship for a number of specialty fuels.

2.1.2 Relative Density (Specific Gravity)

Relative density, or specific gravity, is dimensionless since it is a ratio of the density of a substance to the density of a reference substance, namely water. Density varies with temperature therefore the temperature of the liquid being compared to the reference substance and the temperature of the reference substance, itself, must be given. Relative density can also be expressed in terms of API gravity. The following equation gives the relationship between API gravity and relative density:

$${}^{\circ}\text{API} = \frac{141.5}{\text{Relative Density } (60^{\circ}\text{F})} - 131.5$$

Like density, the specific gravity of a fuel decreases with an increase in temperature. *Figures 2-3* and *2-4* show the effect of temperature on the relative densities of major and specialty fuels.

2.1.3 Thermal Expansion

The effect of temperature on density may also be demonstrated by the thermal expansion of a fuel as it is heated. *Figure 2-5* depicts the expansion of aircraft and missile fuels volume caused by the increase of temperature as compared with their volumes at 15.5°C. Since this volumetric increase tends to be slightly depressed by highly elevated pressures, pressure is specified.

2.1.4 Unit Mass of Fuels

Figures 2-6 and *2-7* provide a general method for determining the appropriate unit mass of aviation gasoline and turbine fuels, respectively, at a given temperature when the relative density at 15.5°C is known.

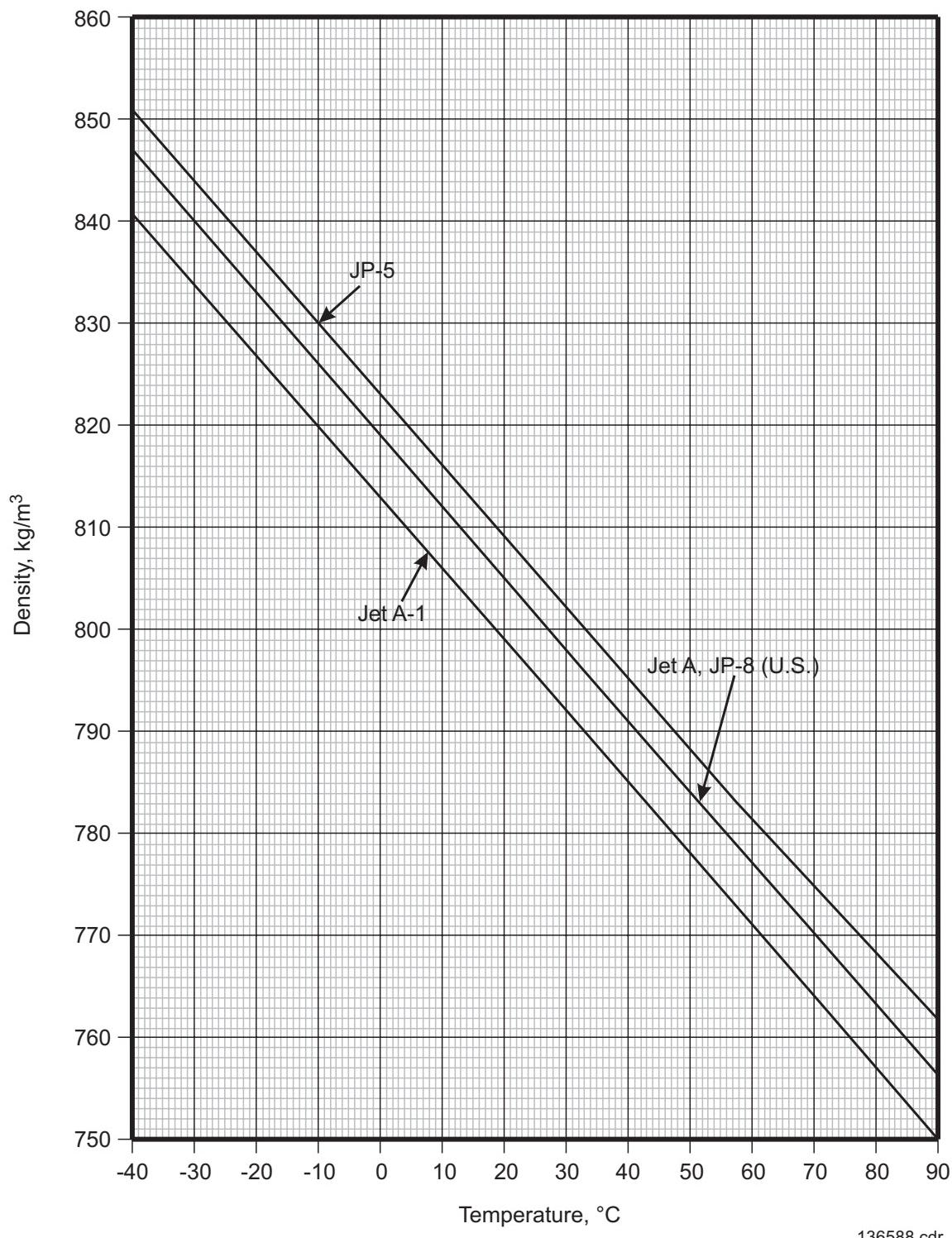


Figure 2-1. Typical Density Versus Temperature for Major Fuels

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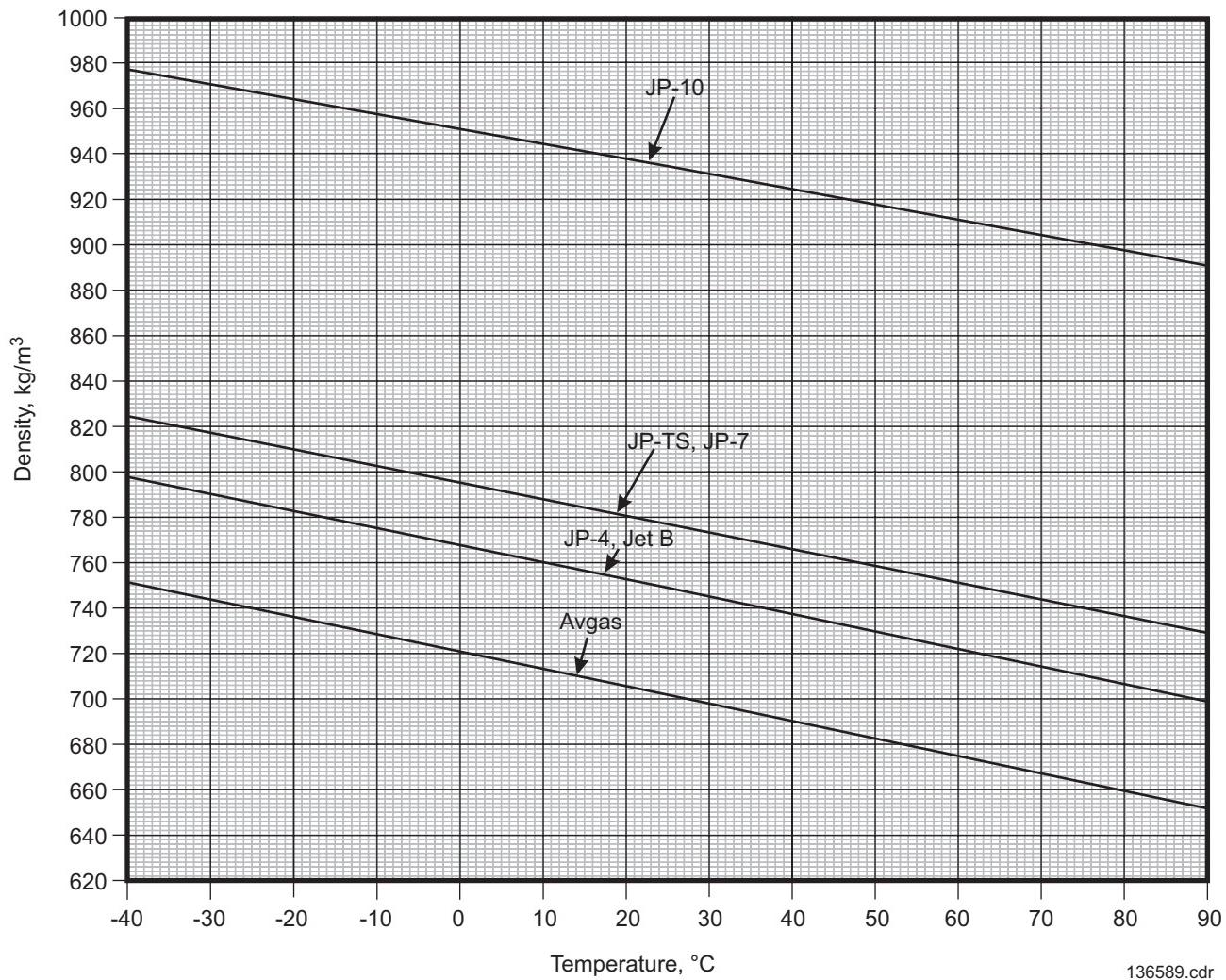


Figure 2-2. Typical Density Versus Temperature for Specialty Fuels

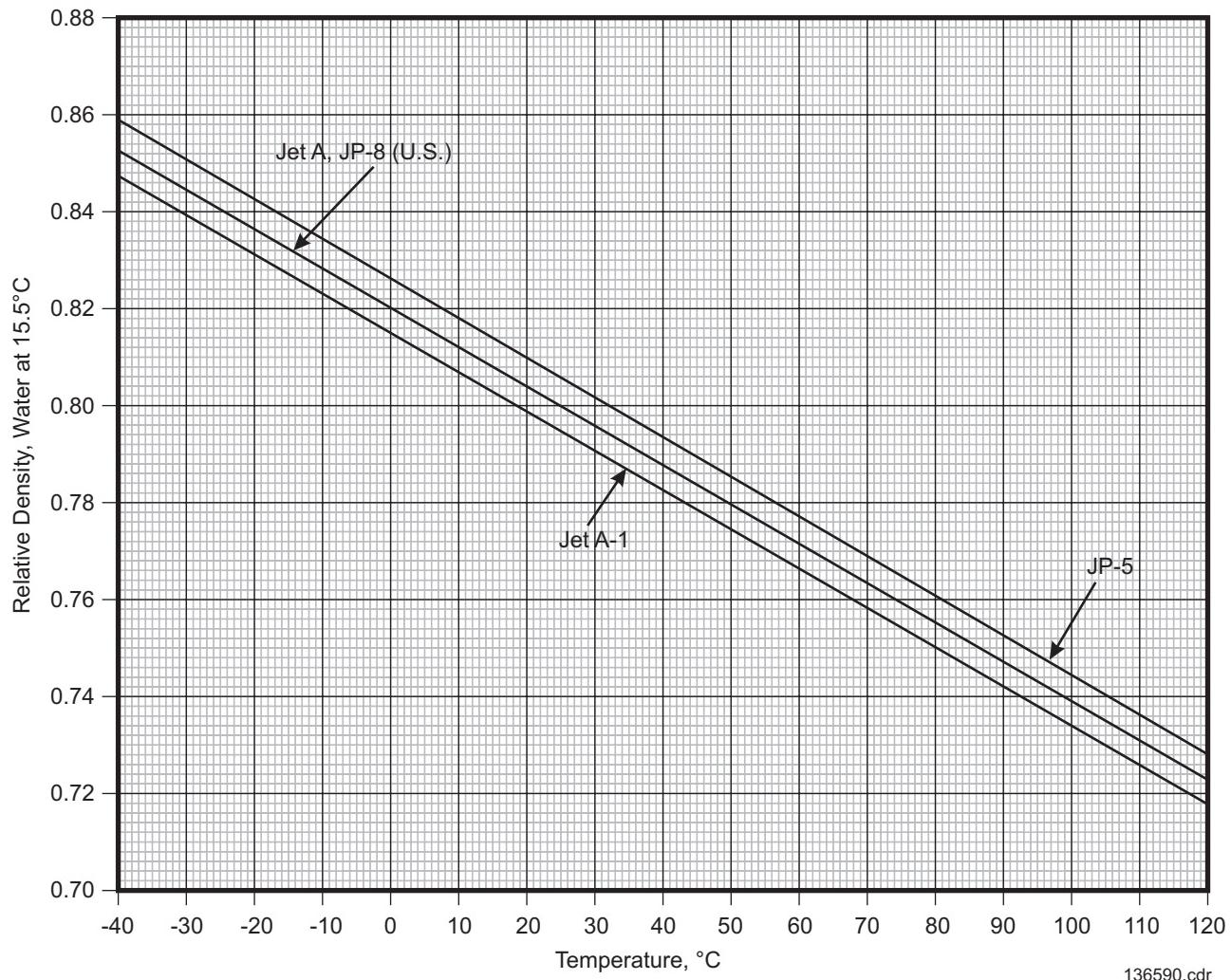


Figure 2-3. Typical Relative Density Versus Temperature for Major Fuels

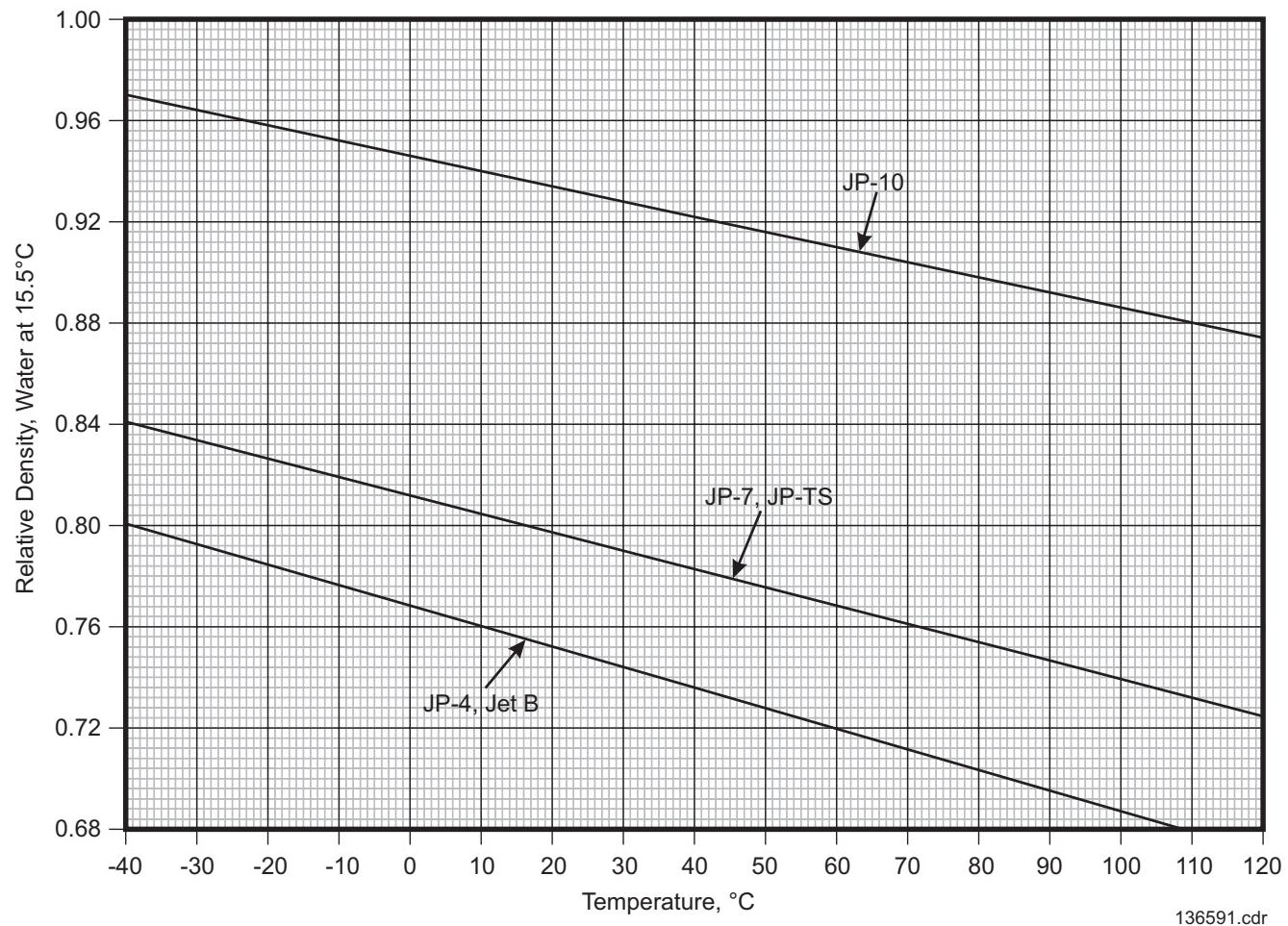


Figure 2-4. Typical Relative Density Versus Temperature for Specialty Fuels

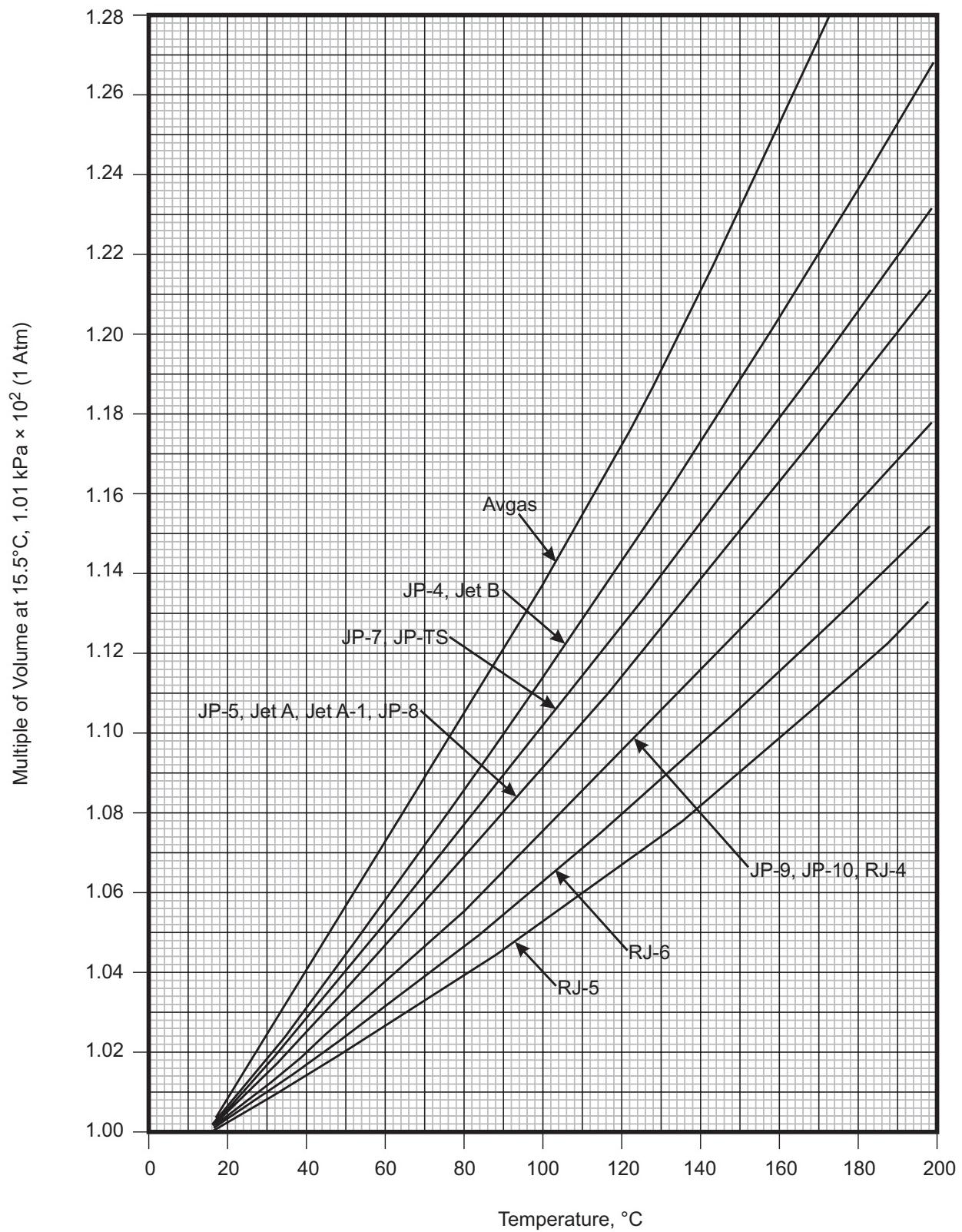


Figure 2-5. Thermal Expansion

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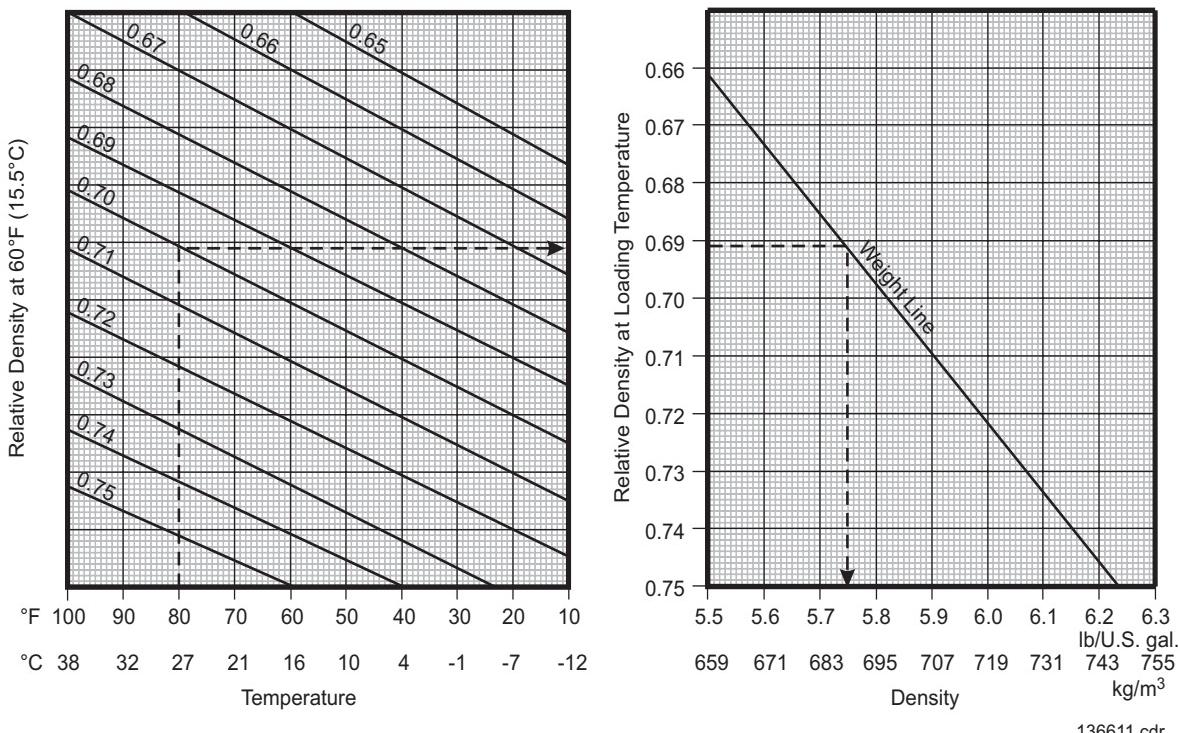


Figure 2-6. Unit Mass of Aviation Gasoline

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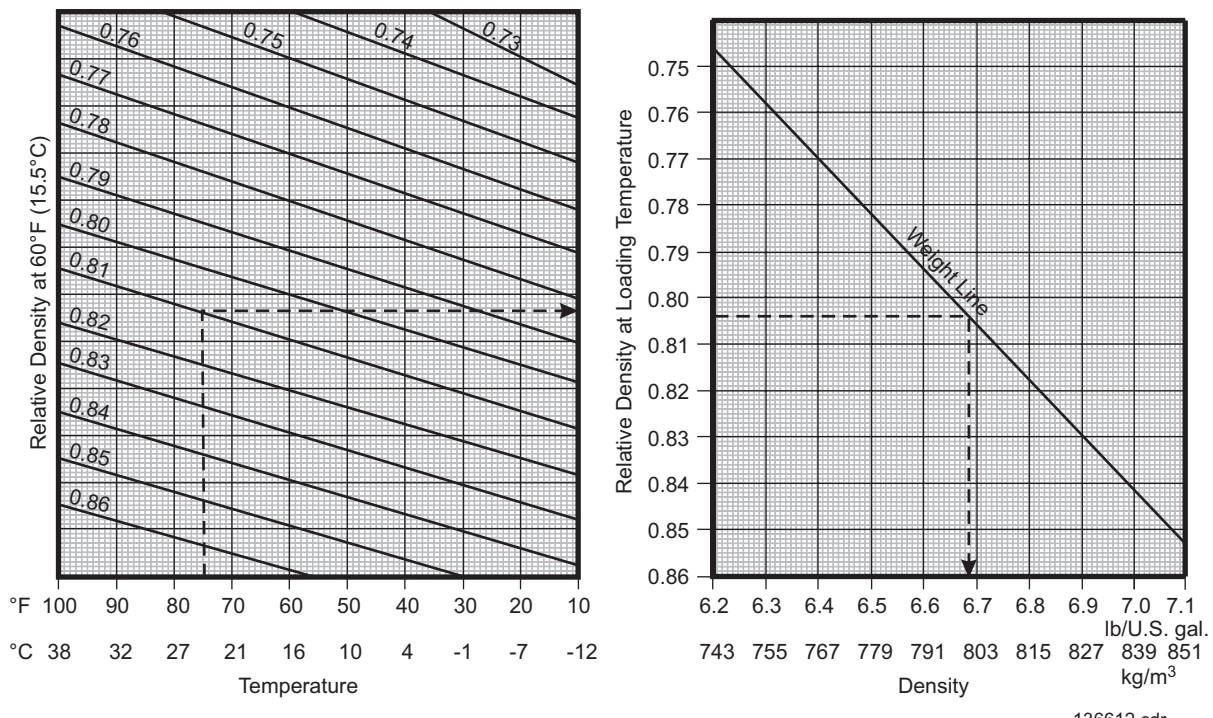


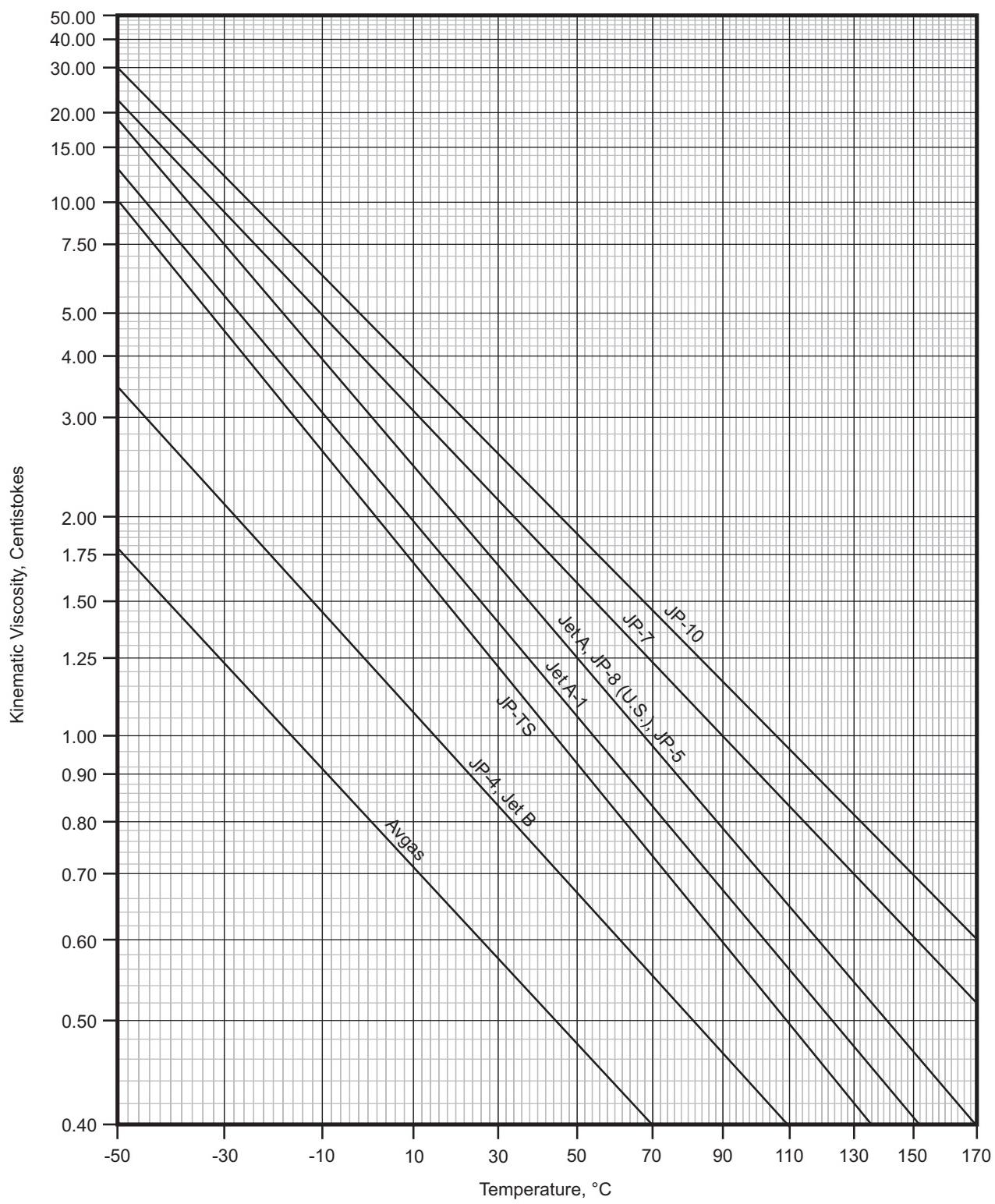
Figure 2-7. Unit Mass of Turbine Fuels

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2.2 VISCOSITY

The viscosity of a fluid is a measure of its internal resistance to motion caused by cohesive forces among the fluid molecules. It is usually determined in combination with density as a function of time. For the fuel system designer, it is a prime factor in calculating pressure drops in lines through its relationship to Reynolds number. The cohesive or interaction forces among the molecules appear as shear stresses between the moving layers of fluid. Absolute viscosity is the shear stress at a point divided by the velocity gradient at that point, and the unit of absolute viscosity is the pascal second. In practice, absolute viscosity is used in conjunction with density, particularly in the calculation of Reynolds number. This relationship between viscosity and density is defined as kinematic viscosity, the ratio of the absolute viscosity of a fluid to the density with both properties measured at the same temperature and pressure.

Kinematic viscosity is usually expressed as cSt, where one cSt is equivalent to one mm²/sec. Since viscosity varies inversely with temperature, lowering the temperature of the fuel has the effect of increasing its viscosity. In fact, many fuel specifications specify maximum viscosity limits at low temperatures to assure pumping and flow capabilities. *Figure 2-8* gives typical kinematic viscosities versus temperature for various fuels plotted on an ASTM chart per ASTM 341-93 (reapproved 1998), an improved version of ASTM D 341-39. The plots on this chart depict a straight line relationship between viscosity and temperature, therefore viscosities can be extrapolated to any desired temperature by connecting known viscosity points at two different temperatures. Caution must be taken not to extend these extrapolations through phase changes.



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Figure 2-8. Kinematic Viscosities Versus Temperature

2.3 SURFACE TENSION

The specific free energy of a liquid surface at interface with another fluid is surface tension. Values for surface tension are usually given when the surface of the liquid is in contact with air. Of importance in gas evolution and solubility, it has a pronounced effect on atomization characteristics of fuels.

Fluids with large cohesive forces among molecules, like those found in water, exhibit high surface tensions. Non-polar fluids such as hydrocarbons have lower internal cohesive forces and lower surface tensions. Surface tensions decrease toward zero as temperature increases, and cohesive forces are overcome until, at the fluid's critical temperature, surface tension ceases to exist. Surface tension can be estimated by using the Ramsey and Shields correlation if density, molecular weight, and the critical temperature of the fluid are known (**Reference 5**). The surface tension data for fuels in **Figure 2-9** have been estimated from the Ramsey and Shields correlation, and the figure shows the reduction of surface tension caused by increasing temperature. Impurities, in particular surfactants, have a very strong effect, causing a reduction in surface tension. In such situations, a direct measure of surface tension is necessary to obtain meaningful data.

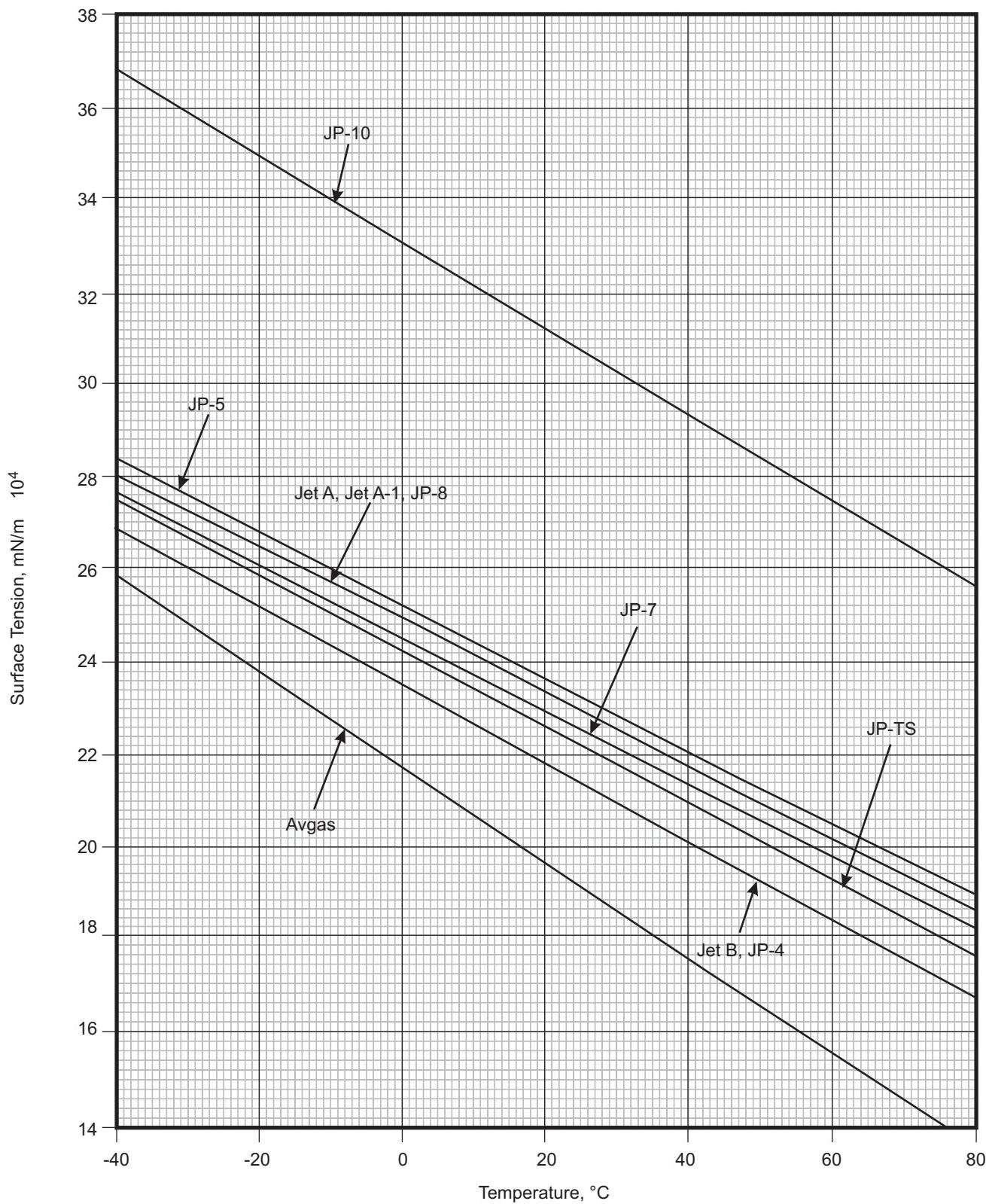


Figure 2-9. Surface Tension Versus Temperature for Fuels

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2.4 VOLATILITY

Volatility is the tendency to change from liquid to vapor. In fuel, volatility is a property that affects its ability to vaporize and form a combustible mixture with air and determines vapor pressure, the pressure exerted by the fuel vapor. Volatility is particularly important to the engine and fuel system designer since it affects vapor and entrainment losses, vapor lock effects on pumping, flammability hazards, and engine-starting characteristics.

2.4.1 ASTM Distillation

Fuel volatility is controlled by specification limits derived from distillation data based on the ASTM D 86 test for distillation of petroleum products. ASTM D 2887, the gas chromatography test for boiling-range distribution of petroleum fractions, is a more precise method, but it is not yet in universal use. Similar to the ASTM D 2892 15-plate distillation column system, D 2887 separates components of fuel into a wider spectrum of hydrocarbons than does D 86. By comparison, the D 86 distillation corresponds to a crude one-plate fractionating device. Nevertheless, D 86 distillation data on volatility can be related to some service performance characteristics. **Figures 2-10** and **2-11** give typical ASTM distillation (ASTM D 86) curves for fuels.

2.4.2 True Vapor Pressure

The vapor pressure of a fuel is defined as the pressure exerted by its vapors in equilibrium with the liquid at a specific temperature, with the absence of air in or over the fuel. In the case of a pure substance, this pressure does not vary with evaporation as long as there is liquid present.

Fairly simple experimental protocols, such as the vapor reflux method, can be used to determine the vapor pressure of pure chemicals or simple mixtures of known chemical compositions. This is the case for missile fuels which are either essentially pure compounds or simple mixtures of such compounds.

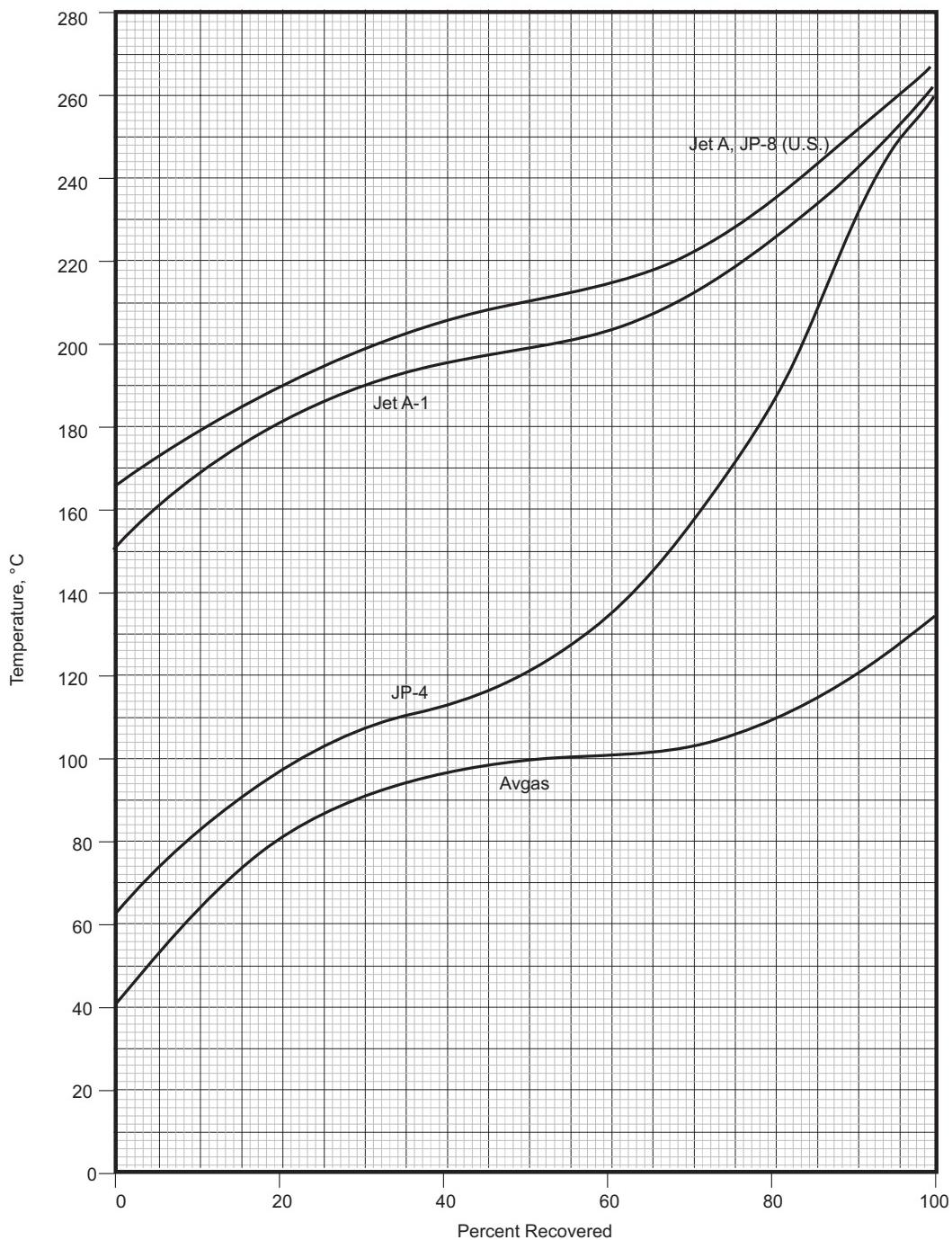
Unlike missile fuels, aviation fuels are complex mixtures of many hydrocarbons of different vapor pressures. Evaporation alters the composition of liquid, and the vapor pressure decreases with the amount evaporated. The measure of the amount of this vaporization is the *vapor/liquid ratio* expressed as the relationship of vapor volume to liquid volume. The true vapor pressure of a mixture such as a petroleum fuel is defined as the pressure exerted as this vapor/liquid ratio approaches zero. It is the maximum pressure attainable at a given temperature since the vapor pressure decreases with increasing vapor/liquid ratio. Although there are several methods available for determining the true vapor pressure of complex hydrocarbon mixtures, they fall into two general categories: the empirical correlation techniques and the experimental techniques. The experimental techniques, namely gas-liquid chromatography and mass spectrometry, may be used, but are expensive and time consuming. The more commonly used empirical correlation techniques are based on two general approaches: the derivation from Reid vapor pressure data as determined by ASTM D 323 or the more accurate ASTM D 2551, and the derivation from distillation data as developed by ASTM D 86 in combination with equilibrium flash vaporization calculations or determinations.

For vapor pressures up to 20 psi, derivation of true vapor pressure by the Reid method is found in **Reference 1**, pages 48 through 109. This methodology is not directly applicable to petroleum fuels of low volatility such as JP-5 and JP-7 in which flash-point temperatures, as measured by ASTM D 93, are used instead of Reid vapor pressures. The above reference includes the flash-point approach along with the determination of changes in true vapor pressure for temperature over a range of vapor-to-liquid ratios.

Distillation data derived from ASTM D 86 is used for determining true vapor pressure by the Edmister technique found in ASTM D 2889, and the British Petroleum method described in **Reference 2**. Using the vapor reflux technique to experimentally determine equilibrium flash vaporization, the JP-7 specification MIL-DTL-38219 (U.S. Air Force), presents a combination of these methods. The Edmister technique is recommended in **Reference 2** for vapor pressures up to 316°C, but is not reliable for fuels having a boiling range of less than 37.8°C (100°F) between 10 percent and 90 percent distilled temperatures. This includes low-volatility fuels such as JP-5 and IP-7. The British Petroleum method and the JP-7 specification method do not have the limitations that are

present with the other empirical methods, and are recommended for precise true vapor pressure determinations when high accuracy is required.

With the exception of JP-5 and JP-7, true vapor pressure curves derived from Reid vapor pressure data for aircraft fuels are found in **Figure 2-12**. Vapor pressures for JP-5 and JP-7 were determined using the JP-7 specification method. **Figure 2-13** gives a vapor pressure curve derived experimentally for JP-10.



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Figure 2-10. *Typical Distillation Curves – ASTM D 86*

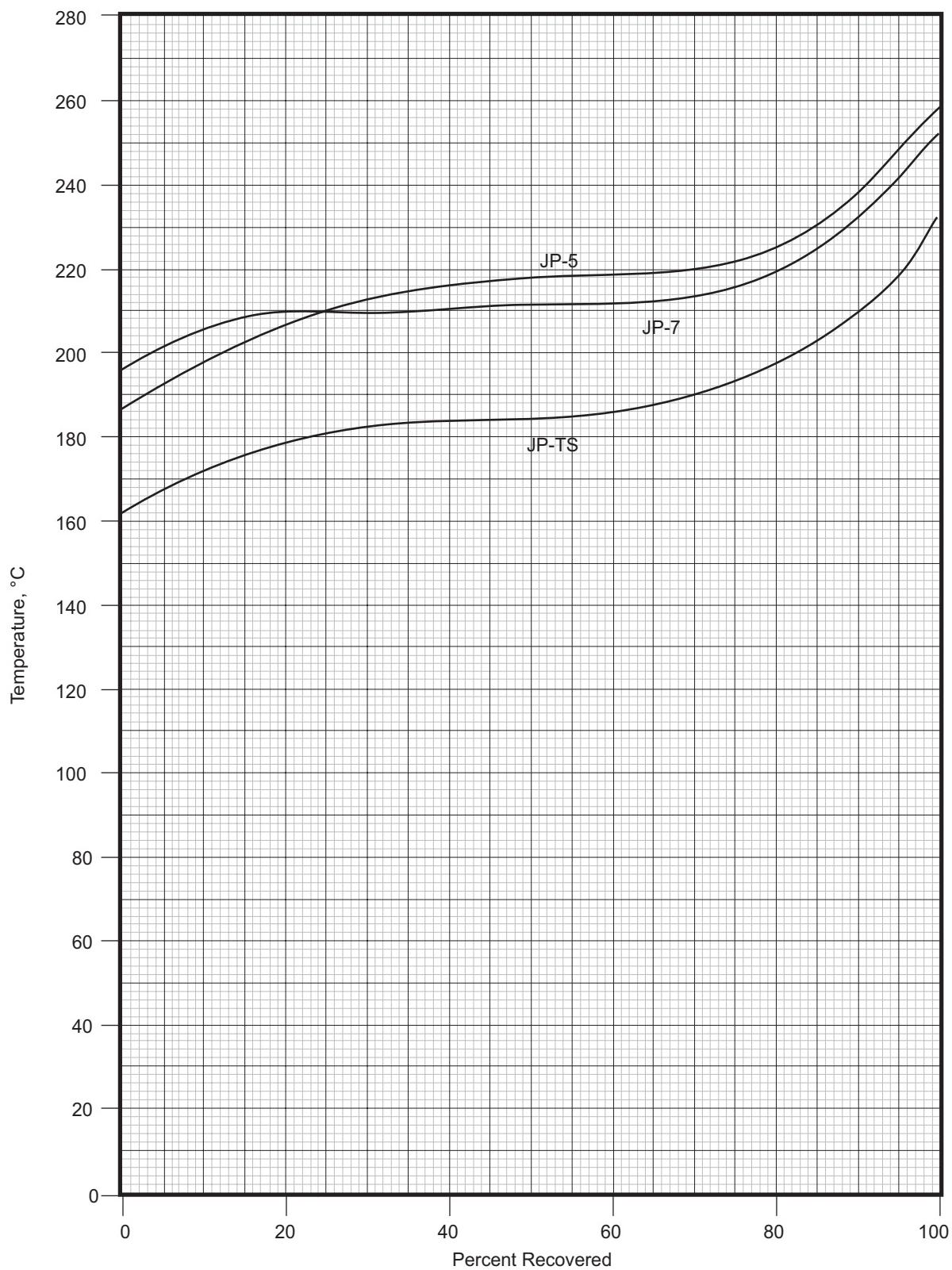


Figure 2-11. Typical Distillation Curves – ASTM D 86

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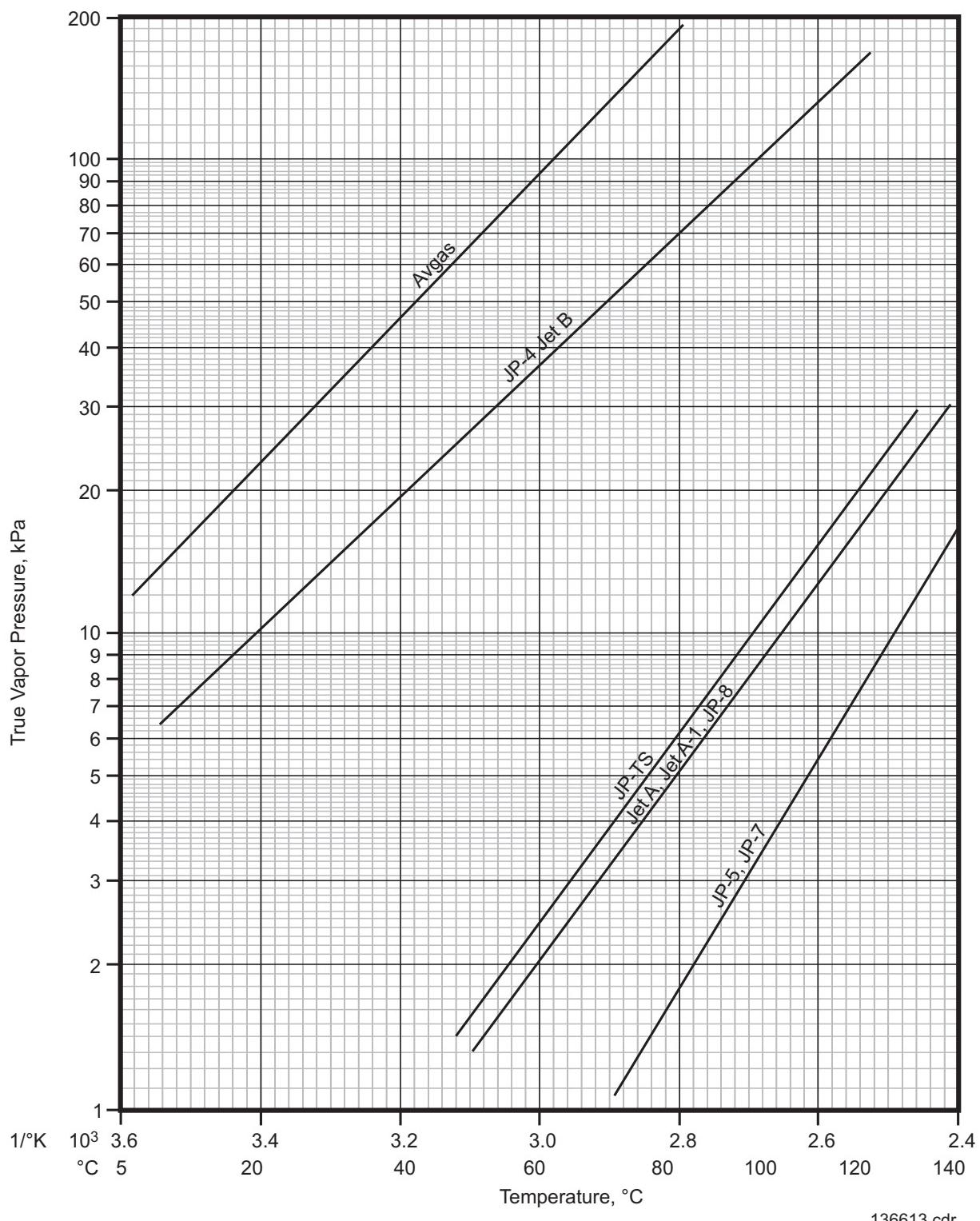


Figure 2-12. Vapor Pressure – Aircraft Fuels

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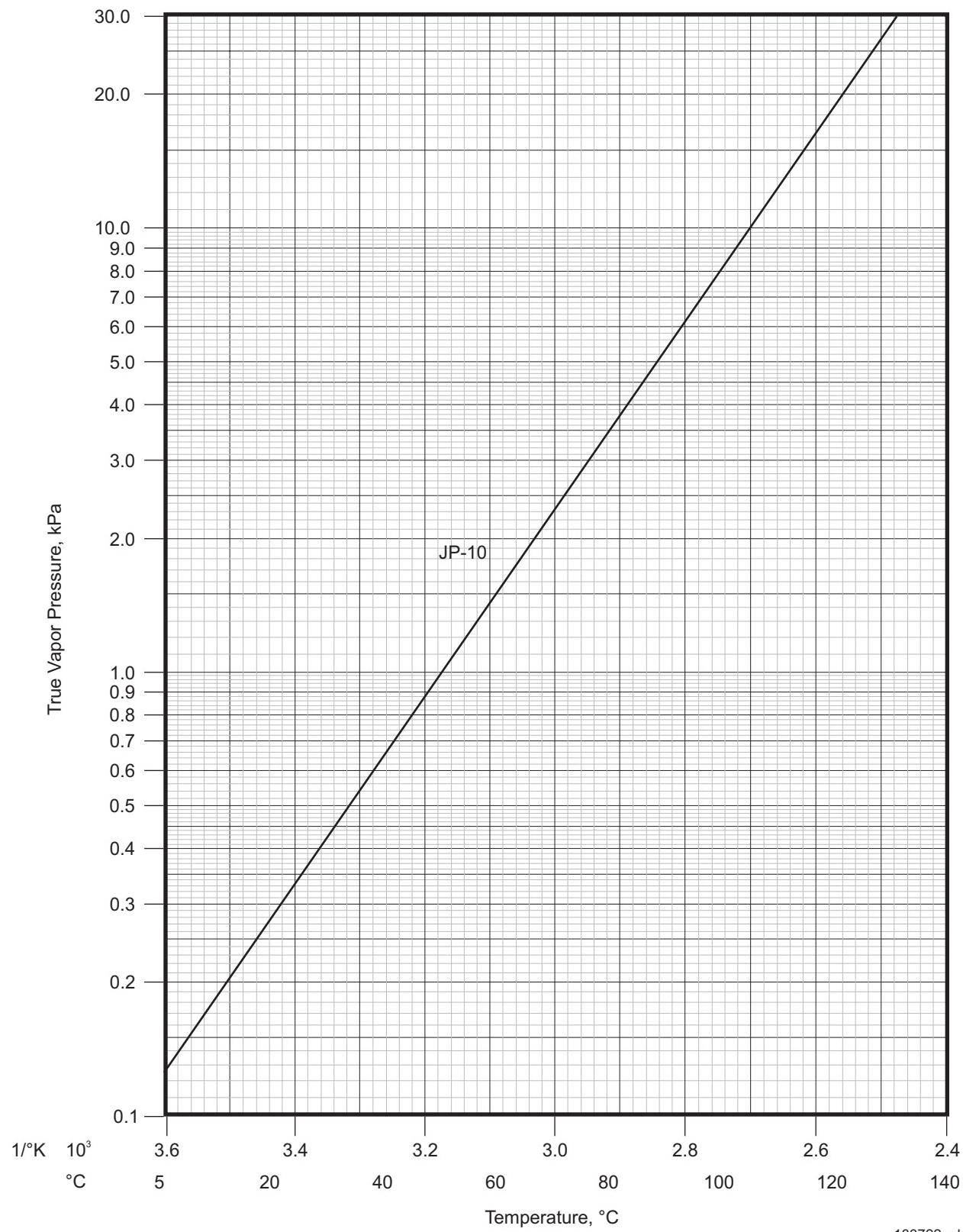


Figure 2-13. Vapor Pressure – Missile Fuels

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2.5 LOW-TEMPERATURE PROPERTIES

The low-temperature properties of fuels must be controlled to insure adequate and reliable system operation, both in flight and on the ground. Basic fuel properties, such as freezing point and viscosity, are important factors in a fuel's pumpability as is the formation of solid materials that can cause flow restrictions. The low-temperature properties of fuels also have a profound effect on the availability of fuels and, therefore, must not be overly restrictive.

In view of the above, the optimal low-temperature criteria for fuels should be based on some direct means of insuring fuel pumpability at the temperatures to which the systems and fuels will be exposed. This approach is attractive due to the ability of dry uncontaminated hydrocarbon fuels, particularly fuel types made up of complex mixtures, to be pumpable below their so called *freezing point*. The freezing point determined under ASTM D 2386 is the temperature at which the visible solid fuel wax particles disappear on warming, the dry fuel having been chilled until wax crystals appear. Despite extensive efforts at developing a suitable pumpability test, the many variables encountered in such tests have obstructed the establishment of specification requirements based on pumpability. The low-temperature characteristics of fuels are, therefore, rather arbitrarily controlled by the freezing point and viscosity limits at -20°C for those fuels which may be marginal from a flow standpoint at the lower temperatures. **Table 2-1** tabulates average freezing points and viscosity values for fuels.

Table 2-1. Low-Temperature Properties of Fuels

	<i>Freezing Point °C</i>	<i>Viscosity at -20°C cSt</i>
Jet A	-45	5.17
Jet A-1	-52.1	3.92
JP-8	-52	NA
JP-5	-51	NA
JP-7	-45.7	6.5
JPTS	-63	6.7 at -40°C
JP-4	-59.4	1.75
Avgas Grade 100LL	-69	NA
JP-10	NA	8 at -18°C
PF-1	-58	23.4 at -54 °C
RP-1	< -36	NA

2.6 THERMAL PROPERTIES

Thermal properties of fuels include those properties of a fuel which are involved in heat-energy transfer to and from the fuel, the heat released or absorbed in the change of state of a fuel, and the heat released in the combustion of the fuel. Including specific heat, thermal conductivity, enthalpy, heat of vaporization, and net heat of combustion, these properties play an important role in the design of an aircraft system and are essential to its performance.

2.6.1 Specific Heat

The specific heat of a fuel is the amount of heat-energy transferred into or out of a unit mass of the fuel when increasing or decreasing its temperature. In fuel system analysis, specific heats are used in the calculation of heat-transfer, using the fuel as a coolant or as a heat sink. Specific heat is given in terms of kilo joules per kilogram

Kelvin (kJ/kg K) in the IEE/ASTM-SI-10 Standard for Use of the International System of Units (SI): The Modern METRIC System.

Figures 2-14 and 2-15 give the specific heats of aircraft fuels and JP-10 plotted against temperature. These data were derived from experimental and calculated methods. The experimental data were developed using a differential scanning calorimeter, while the bulk of the determinations were calculated from a correlation published by J. B. Maxwell using averaged fuel gravity and distillation data (**Reference 32**).

2.6.2 Thermal Conductivity

The thermal conductivity of a fuel is the property that controls the rate at which heat can flow by conduction through that fuel and is expressed as watts per meter Kelvin (W/m K). It is used extensively in heat-transfer calculations when fuel temperature is elevated in heat exchangers, used as a heat sink, when fuel is heated or cooled in flight or on the ground, or whenever there is a temperature gradient within the fuel.

In **Figure 2-16**, thermal conductivity is plotted as a function of temperature for hydrocarbon fuels and JP-10. The common fuel curve and JP-10 curve are based on an extensive review of all experimental data, and differ from Figure 24 in the 1983 CRC Handbook of Aviation Fuel Properties.

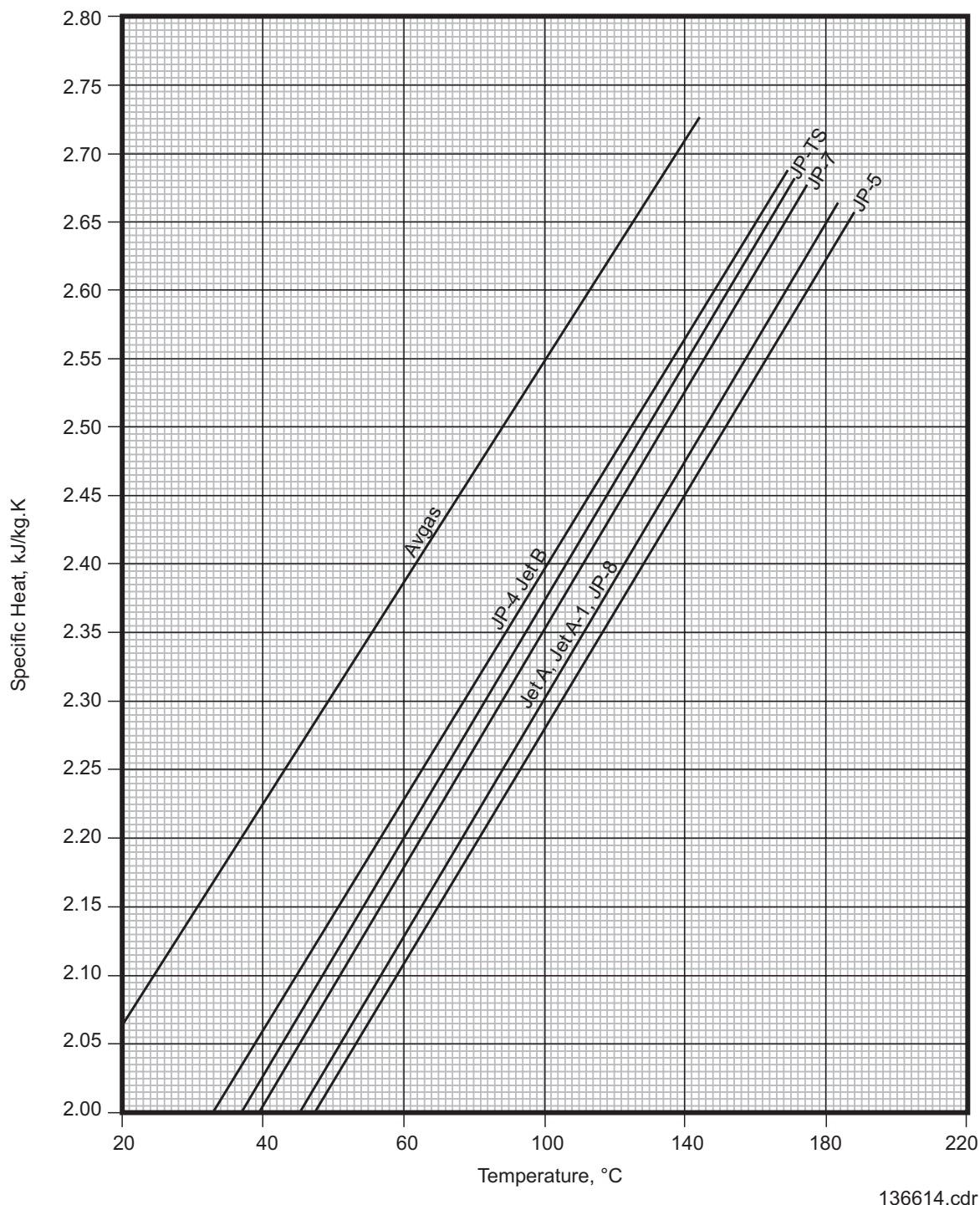
2.6.3 Enthalpy

Enthalpy is the heat energy required to bring a fuel from one reference state to another state. It is a function of the integral of the specific heat between the two states, and any latent heat of vaporization that was required in the interval. Enthalpy is quantified in terms of kJ/kg.

Figures 2-17 and 2-18 are enthalpy diagrams for typical JP-4 and JP-5, respectively. In these figures, the saturated liquid curve represents the heat that can be absorbed in the liquid phase alone, and the saturated vapor curves depict the heat absorbed to completely vaporize the fuel. The intermediate area denotes partial vaporization, while the curves above this saturated vaporization line indicate super-heated vapor. The line of constant pressure provides the pressure relationship to determine the state of vaporization of the fuel for the addition of a given amount of heat.

2.6.4 Heat of Vaporization

The heat of vaporization is the amount of heat added to vaporize a unit weight of a liquid at a constant pressure below the critical point. As the pressure increases, the heat of vaporization decreases and at the critical point, the heat of vaporization becomes zero. Using the equations in **Reference 27**, the heat of vaporization can be calculated at sea level pressure. At other temperatures and pressures, a general method outlined in **Reference 42** must be used. **Figure 2-19** is a plot of the heat of vaporization of various fuels versus temperature in kJ/kg.



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Figure 2-14. Typical Specific Heat Versus Temperature for Aircraft Fuels

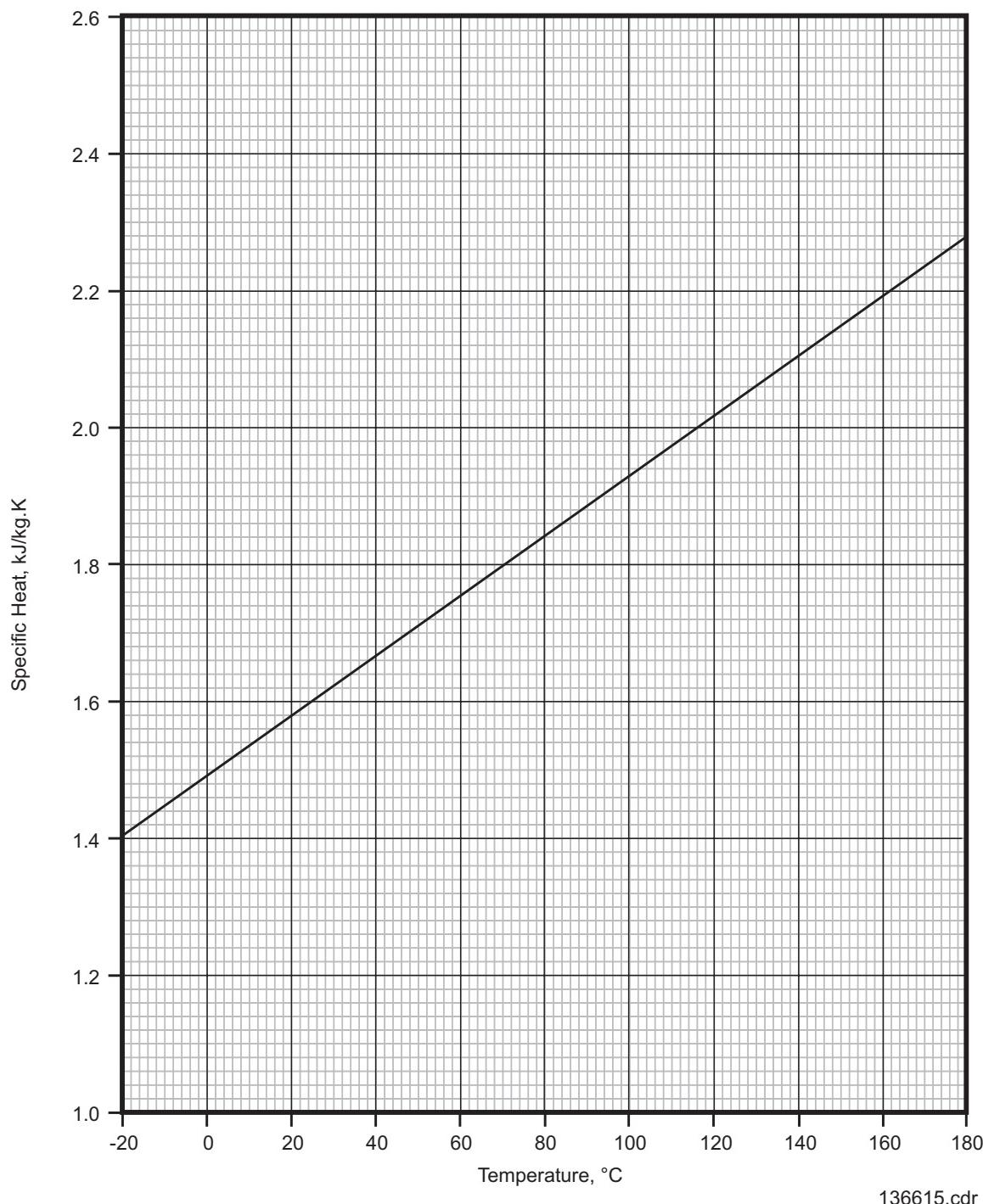


Figure 2-15. Typical Specific Heat Versus Temperature for JP-10

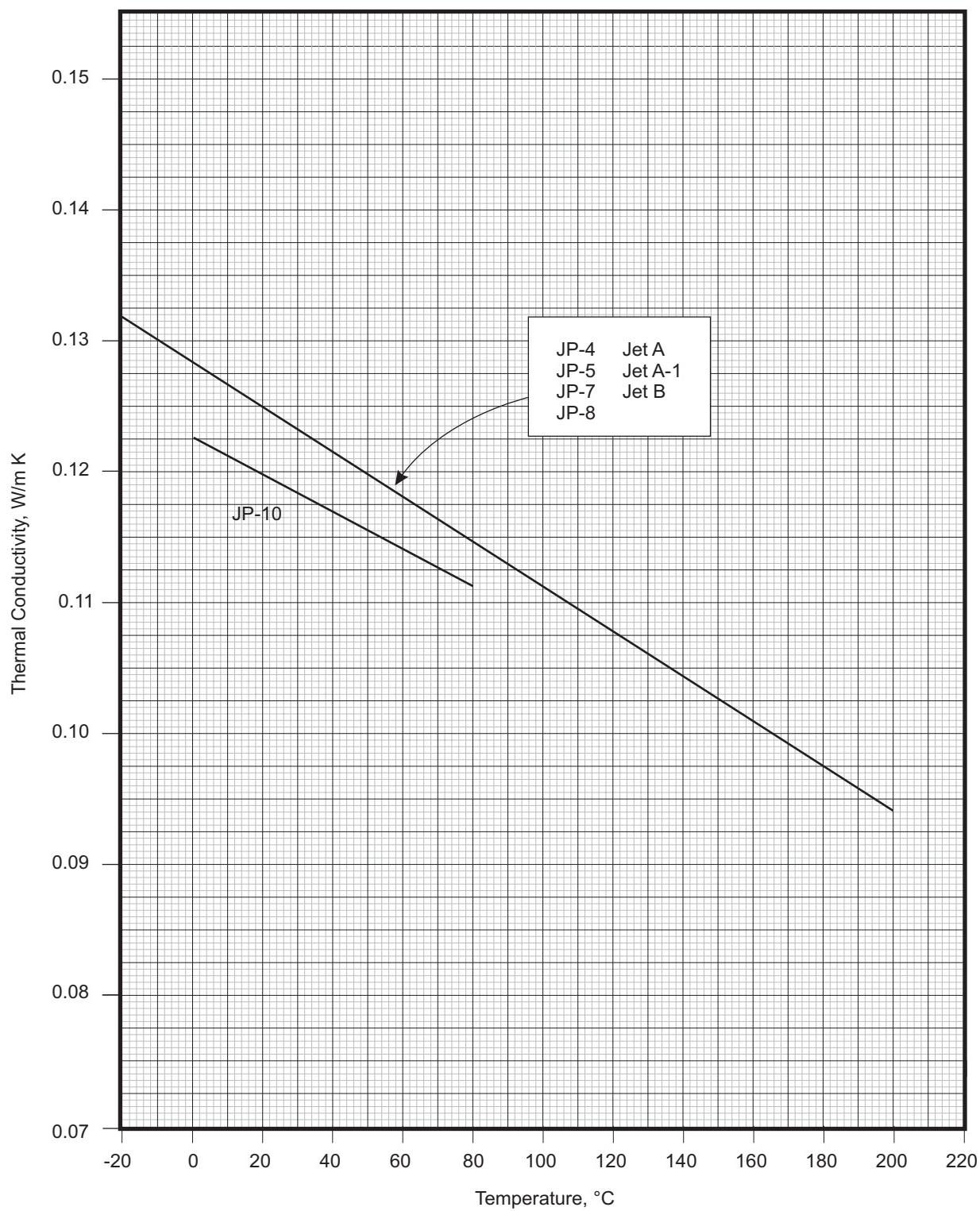


Figure 2-16. Thermal Conductivity of Hydrocarbon-Based Fuels

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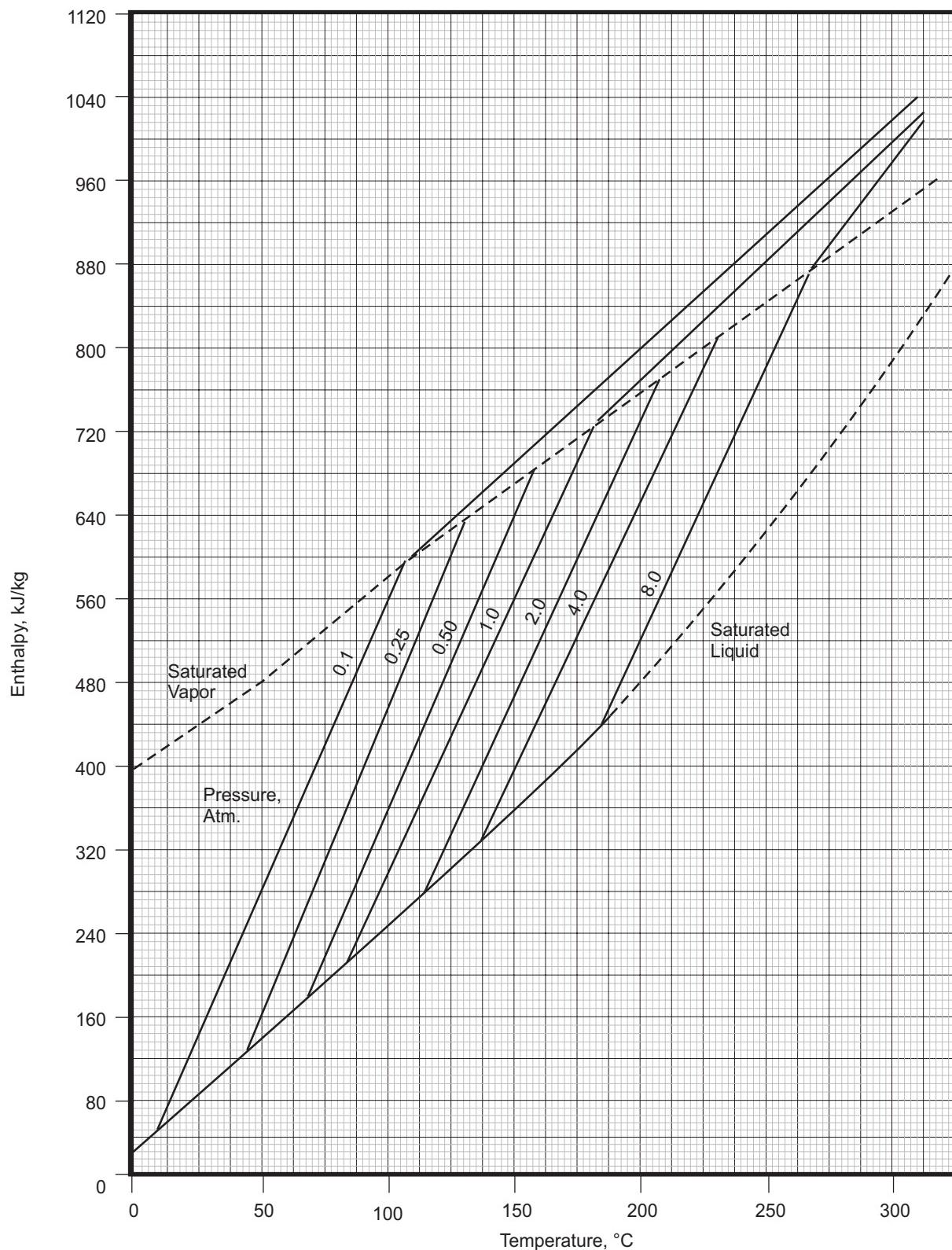


Figure 2-17. Enthalpy Diagram – JP-4

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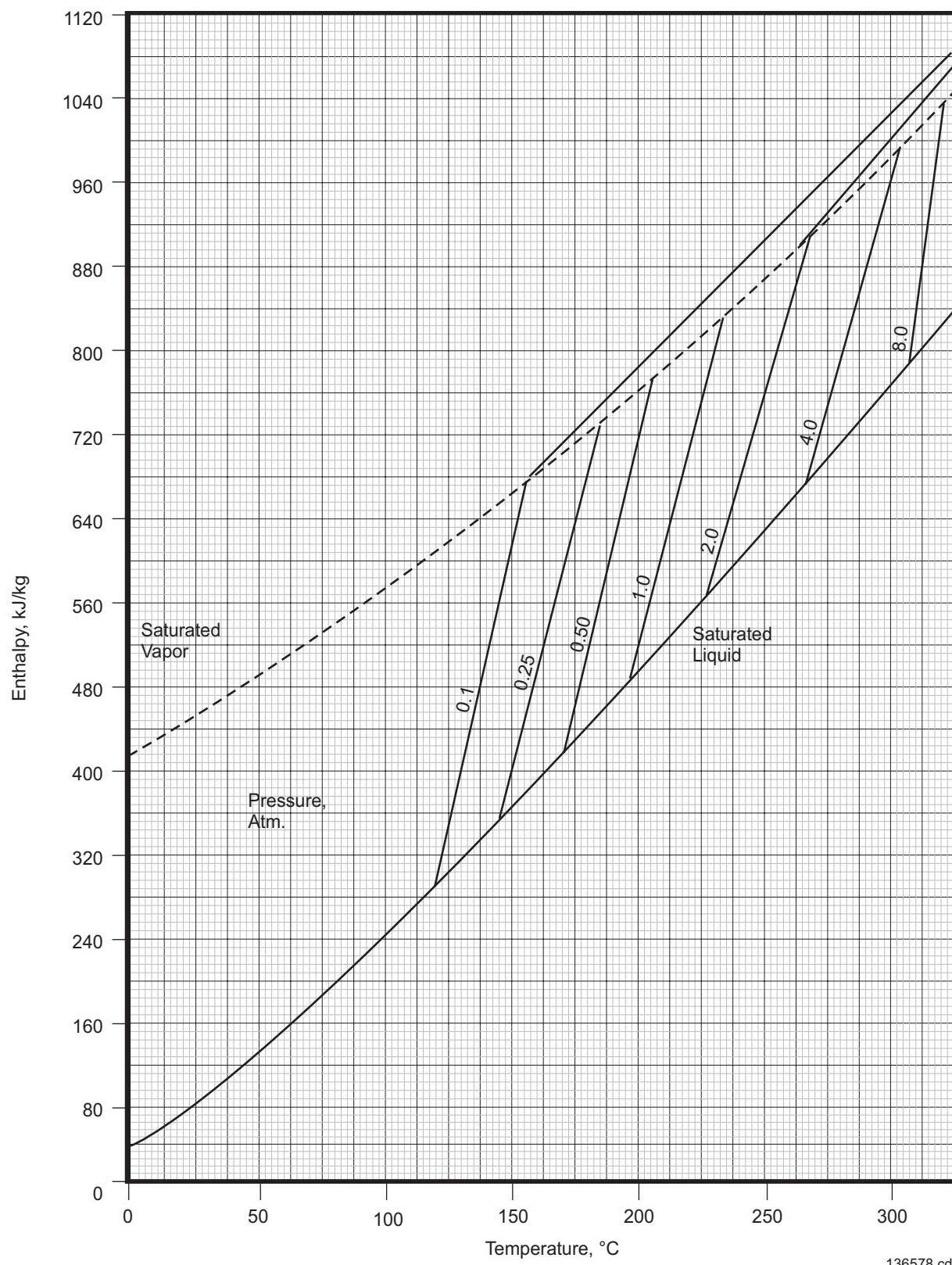


Figure 2-18. Enthalpy Diagram – JP-5

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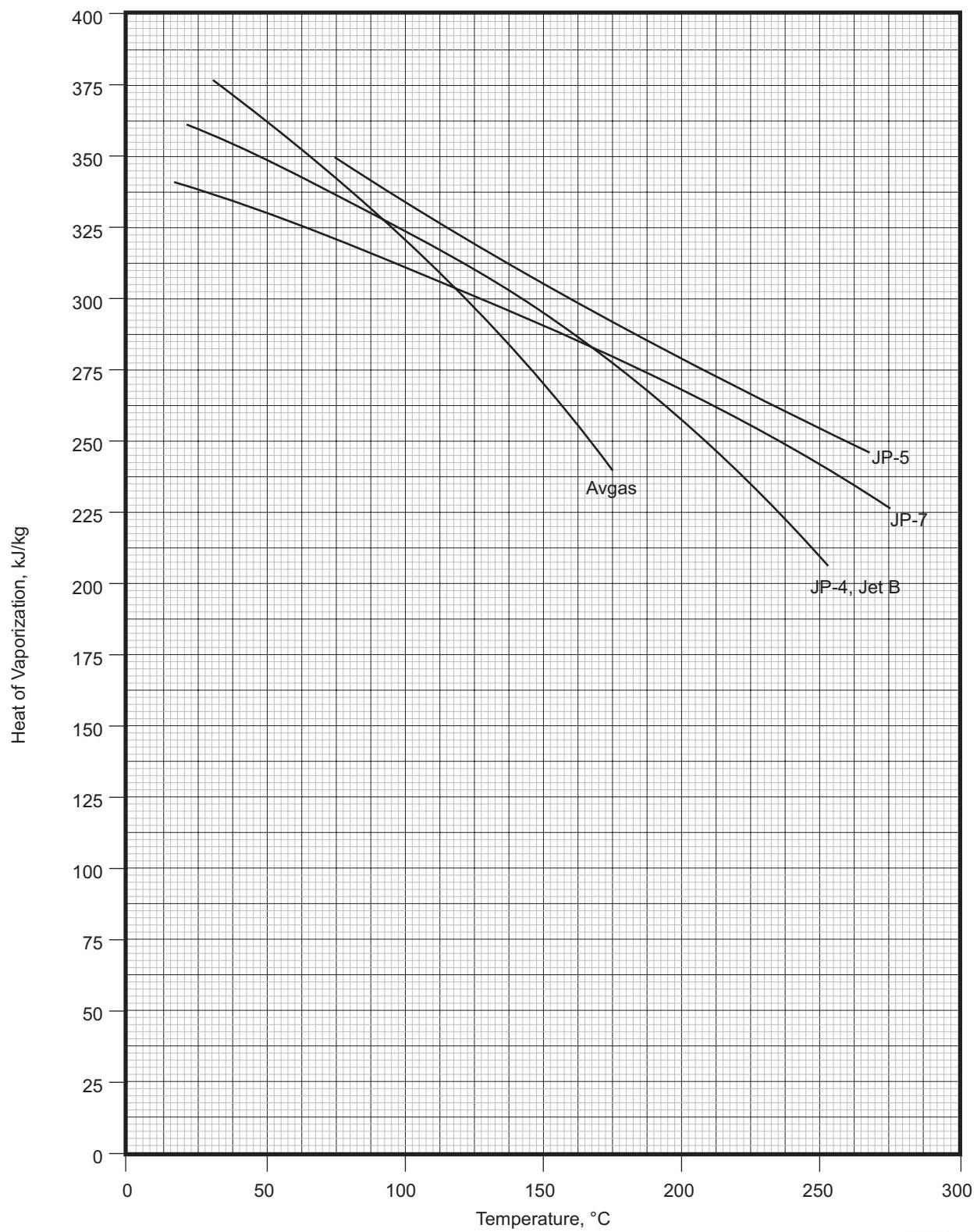


Figure 2-19. Heat of Vaporization for Various Hydrocarbons

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2.6.5 Heat of Combustion (Specific Energy)

When a unit weight is burned in a bomb-type calorimeter under controlled conditions to produce gaseous carbon dioxide and liquid water containing sulfuric and nitric acids, the energy stored in fuel is released as heat. The gross heat of combustion, or specific energy, of the fuel in terms of mega joules per kilogram (MJ/kg) or BTU per pound (BTU/lb), is calculated from the rise of temperature after suitable corrections are made. In an aircraft gas turbine, the product water from combustion leaves in the vapor phase. The proper basis for comparison of aircraft fuels is net heat of combustion, established when the heat of water vaporization determined from the hydrogen content of the fuel is subtracted from the gross heat of combustion.

2.6.5.1 Net Heat of Combustion of Aircraft Fuels

The net heat of combustion per unit weight is important to aircraft performance. Empirical methods ASTM D 1405 and D 3338 are used to estimate the heat of combustion of some aircraft fuels. Experimental methods ASTM D 240 and D 2382 can also be used and are expressly required in some specifications. In the ASTM Standard for Metric Practice, the heat of combustion is quantified in MJ/kg.

Table 2-2 presents average net heat of combustion data for the various aircraft fuels.

Table 2-2. Typical Net Heat of Combustion

<i>Aircraft Fuels</i>	<i>Net Heat of Combustion (MJ/kg)</i>
Jet A	43.2
Jet A-1	43.2
JP-8 (U.S.)	43.3
JP-5	43.1
JP-7	43.5
JPTS	43.4
JP-4	43.9
Avgas Grade 100LL	44.0

2.6.5.2 Net Heat of Combustion of Missile Fuels

The heat of combustion per unit volume is an important factor in missile performance. Experimental methods ASTM D 240 and D 2382 are used to determine the basic values of heat release per unit volume, depending upon the density of a particular fuel. In the ASTM Standard for Metric Practice, the volumetric heating value is quantified in terms of mega joules per cubic meter (MJ/m³). For JP-10, the average net heat of combustion per unit volume is 39,543 MJ/m³, and the net heat of combustion per unit weight is 42.2 MJ/kg.

2.7 ELECTRICAL CHARACTERISTICS

Fuels have electrical characteristics that are important to aircraft and fuel system designers. The conductivity of a fuel plays a primary role in a fuel's electrostatic charge as it flows through a system and the dielectric properties relate to the way a fluid varies the capacitive reactance of a pair of parallel electrodes, and is the key to the design of fuel gauges.

2.7.1 Dielectric Constant (Permitivity)

The dielectric constant of a fuel is experimentally determined by establishing the ratio of the electrical capacitance of a device filled with the fuel as compared with the electrical capacitance of the same device when filled with air. Measurements of the dielectric constant of a fuel at various temperatures show that the dielectric constant is a linear function of temperature, decreasing with increasing temperature and varying with the applied frequency. *Figure 2-20* illustrates the relationship of dielectric constant versus temperature of various fuels for data collected at 400 Hz, the most used frequency in commercial and military aircraft. Fuel gauges must be calibrated for the particular fuel being measured.

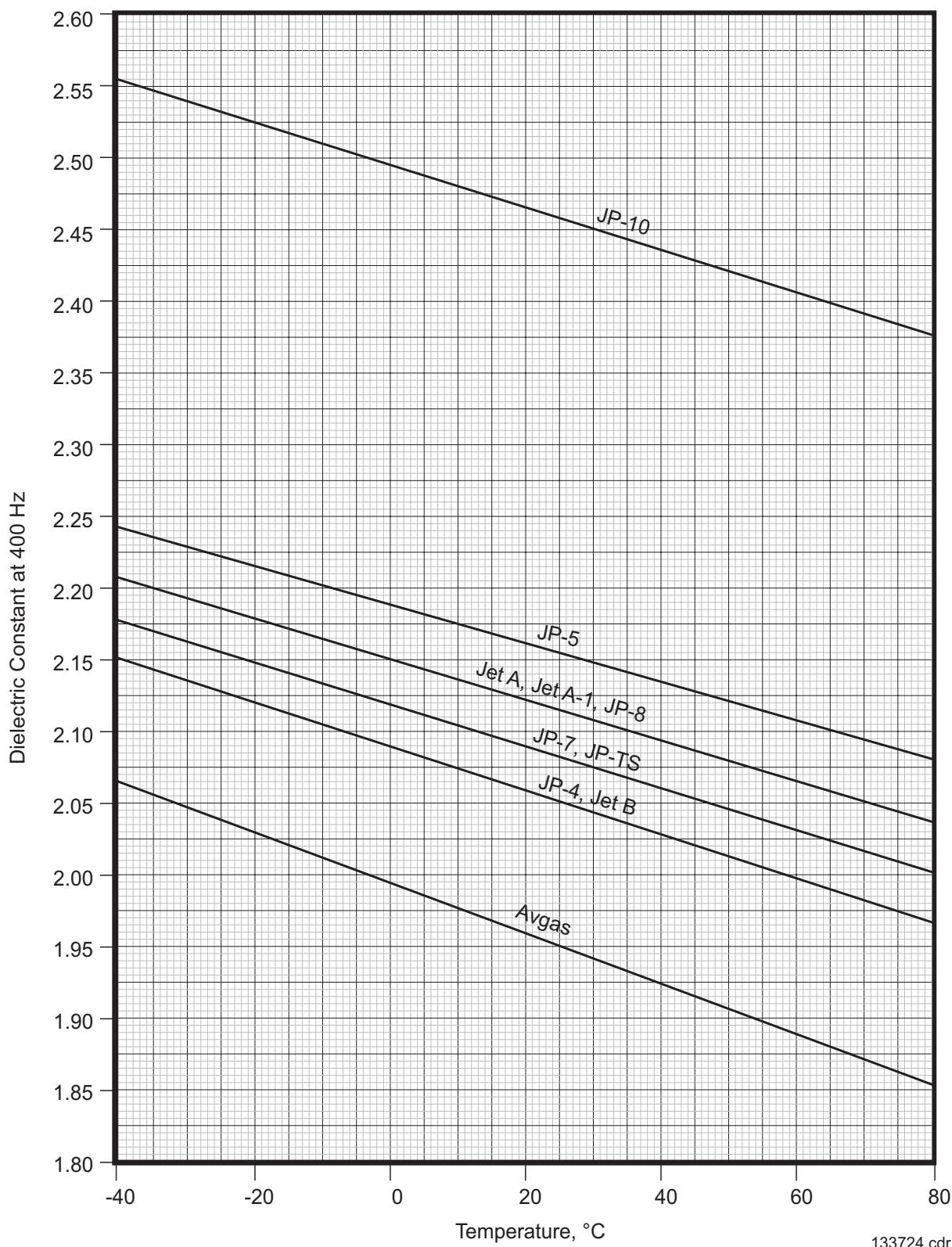


Figure 2-20. Dielectric Constant Versus Temperature

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2.7.2 Electrical Conductivity

Pure hydrocarbons and mixtures of hydrocarbons, such as fuels, are essentially non-conductors of electricity. In practice, however, they always contain trace amounts of materials which increase their conductivity to a lesser or greater extent, depending upon the chemical nature and the concentration of the impurities. In most cases, the conductivity of the fuels is still very low. In any event, this low conductivity is the fundamental property that can cause a very hazardous situation to arise when handling flowing fuels.

Due to a shearing mechanism called *charge separation*, a flowing fuel tends to become electrically charged. This phenomenon can cause the development of high levels of electrostatic charges within the fuel which cannot be dissipated due to the low conductivity of the fuel. These free charges can build up to levels high enough to cause static discharges through the vapors in tanks. Depending upon the composition of the vapor phase, ignition may occur. The phenomena are highly complex and, depending upon the system and conditions encountered, may involve a multitude of variables. Factors like high contact areas encountered in filter separators, relaxation time required for charge dissipation, fuel system design, protruding devices in flow channels, impurity levels in the fuel, and many others influence the degree of hazard. At the root of the problem, however, is the fundamental low conductivity of fuels which, in most cases, is in the range of 0.1 to 5.0 picoSiemens/meter (pS/m), even with trace impurities present.

Notwithstanding the development of various devices to decrease and measure the charge buildup in fuels, the most successful approach has been the introduction of an additive to increase the overall conductivity of the fuel. A minimum of 50 pS/m will furnish adequate conductivity for handling safety. The maximum limit of 600 pS/m is set low enough to prevent malfunctions of fuel quantity capacitance gauges. Fuels will generally show decreased conductivities at lower temperatures. Due to this factor, most fuels are treated with enough additive to produce a conductivity of 175 to 200 pS/m at 15.5°C, so that they will still retain conductivities of at least 50 pS/m at lower temperatures.

Temperature versus conductivity behavior is variable. **Figure 2-21** shows a typical change in conductivity based upon the variability of jet kerosine fuels' temperatures. Low temperature behavior for fuels containing static dissipator additive is roughly defined by fuel viscosity where less viscous fuels such as Jet B/JP-4 show less change in conductivity with temperature. Temperature-conductivity behavior is also affected by trace materials present in fuels. Laboratory clay filtration, for example, can change the temperature-conductivity behavior of many fuels. If corrosion inhibitor/lubricity additives are present, the fuel will exhibit more loss in conductivity at lower temperatures. Since the nature of the materials in fuels without SDA is variable and undefined, the curve in **Figure 2-21** shown for fuel without additive should thus be viewed only as generally representative of this behavior.

A complete review of the generation and dissipation of electrostatic charge and a selected literature survey can be found in **Reference 13**.

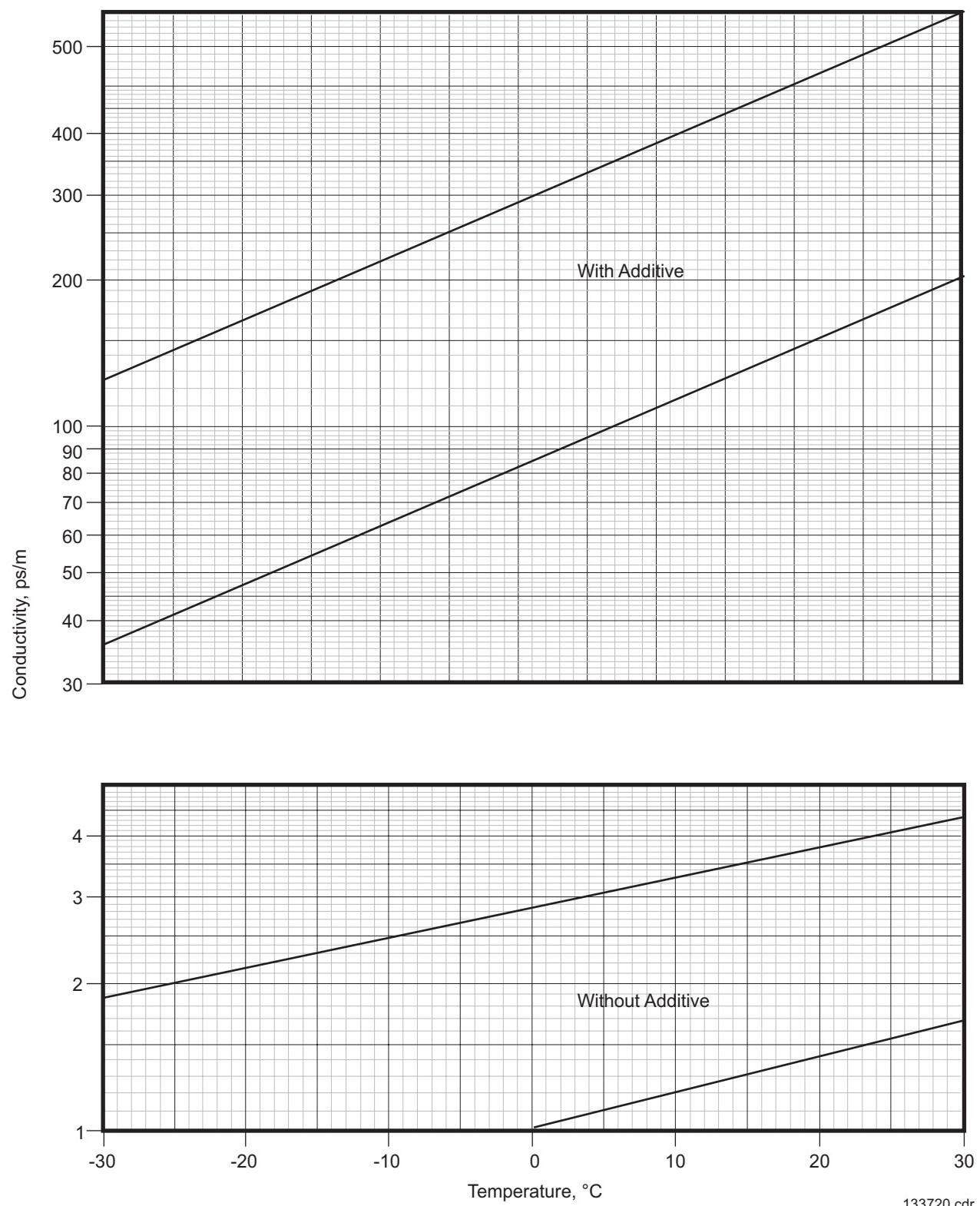


Figure 2-21. Typical Range of Conductivity

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2.8 FLAMMABILITY AND IGNITION CHARACTERISTICS

Due to their importance in the safety aspects of system design and performance of propulsion devices, the combustion properties of fuels have been studied extensively. The basic components necessary for combustion are fuel vapor, air, and an ignition source. In actuality, a multitude of variables and influencing factors must be taken into consideration. Because a complete review of this subject is beyond the scope of this report, only selected data are presented. The primary goal of this report is to establish relationships among the various fuels. The data should be used with caution, since each specific situation may have other factors that must be considered. Discussions of the influences of non-equilibrium conditions and the effect of system design are found in *Reference 11* through *Reference 22*.

Table 2-3 presents typical flammability and ignition properties of fuels. These values are examples as values vary significantly within the same fuel specification.

Table 2-3. Typical Flammability and Ignition Properties

Property	Jet A/JP-8	JP-5	JP-7	JP-10	Avgas 100	JP-4/Jet B
Flammability Concentration Limits ¹ (vol %)						
Lower (Lean) Limit	0.6	0.6	0.6		1.2	1.3
Upper (Rich) Limit	4.7	4.6	4.6		7	8
Flammability Temperature Limits (°C)						
Lower (Lean) Limit ² (1 atm)	53	64	60		-44	-23
Upper (Rich) Limit (1 atm)	77	102	100		-12	18
Min Electric Spark Ignition Energy (mJ) ¹	0.2 to 1	0.2 to 1	0.2 to 1		0.2 to 1	0.2 to 1
Approximate Burning Velocity ¹ (m/s)	0.3 to 0.6	0.3 to 0.6	0.3 to 0.6		0.3 to 0.6	0.3 to 0.6
Autoignition Temperature (°C) (1 atm)	238	241	241	245	433	246

¹ Fuel vapors in air.

² Tag Closed Cup flash point data. Experimental flash points are generally higher than limit data.

2.8.1 Flash Point Test Methods

The flash point of aviation fuels is measured using a number of standard test methods (**Table 2-4**) in which a specimen is placed in a sample container and the fuel temperature is increased. The fuel vapor is periodically exposed to a flame and observed for the onset of combustion. The lowest temperature at which the vapors ignite is taken as the flash point.

Table 2-4. Comparison of Flash Point Test Methods

Method	Method Title	Test Method Standard Deviation at 38 °C ¹	Measured Flash Point °C for n-Decane	Measured Flash Point °C for n-Undecane
ASTM D 56	Standard Test Method for Flash Point by Tag Closed Tester	1.6	50.9	67.1
ASTM D 93	Standard Test Method for Flash Point by Pensky-Martens Closed Tester	0.97	52.8	68.7
ASTM D 3828	Standard Test Method for Flash Point by Small Scale Tester	0.74	NA	NA
IP 170	Petroleum Products-Determination of Flash Point - Abel Closed Cup Method	0.54	NA	NA

¹ Test method reproducibility divided by 2.77.

Different test methods can produce different results. **Table 2-4** illustrates this by comparing the higher flash points measured by ASTM D 93 to those of ASTM D 56 for both n-decane and n-undecane calibration standards.

2.8.2 Average Flash Points for Various Fuels

Flash point is the best known and most widely used property for the evaluation of the flammability hazard of combustible liquids. Average flash point values for various fuels are shown in **Table 2-5** as is the variability of flash point values expressed in terms of the standard deviation of the average value where data is available. This includes both the variability of the flash point test method (**Table 2-4**) and the variability resulting from other factors such as specification requirements, refinery quality control strategies, and differences in fuel geographical manufacturing practices. With the demand for gasoline higher than the call for distillate in North America, production practices differ from those in Europe, where the demands for gasoline and distillate are more balanced. As a consequence, U.S. produced fuels tend to have higher flash points than European jet fuels, even though they have the same flash point specification requirement.

Table 2-5. Average Flash Points

	<i>Average Flash Point °C</i>	<i>Variability of Flash Point: Standard Deviation Around the Average °C</i>
Jet A	51.2	5.8
Jet A-1	42.2	2.5
JP-8	48.9	5.9
JP-5	63.3	2
JP-7	70	NA
JPTS	49	NA
JP-10	57	NA
PF-1	25	NA
RP-1	68	NA

2.8.3 Flammability Limits Versus Altitude

Self-sustained combustion occurs within certain ranges of fuel vapor/air ratios which are functions of temperature and pressure. Therefore at any given pressure, a fuel will have a lean flammability temperature limit, and at a higher temperature, a rich flammability limit. Outside these limits, combustion will not occur if the system is in equilibrium with no spray or mist present. **Figure 2-22** gives the flammability temperature limits for fuel versus altitude in meters.

2.8.4 Effects of Dynamics on Flammability Limits

Equilibrium conditions for the determination of flammability limits must only be used for comparative purposes. In actual practice, tank movement or flow through nozzles will affect these limits by the formation of mists and droplets. **Figure 2-23** depicts the change of the equilibrium limits due to a sloshing situation in a tank. Here, pressure rises due to ignition which occurred at temperatures well below the equilibrium flammability limits. The rich limits are not affected, however, since dynamic situations only add fuel to an already rich condition.

2.8.5 Effect of Air Release on Flammability Limits

At sea level conditions, fuels normally contain a quantity of dissolved air. Since oxygen has higher solubility than nitrogen, when pressure is decreased and altitude increased, oxygen-rich gas is released into the vapor phase over the tank. This additional oxygen will increase the rich flammability markedly and, for all practical purposes, the lower limit is unchanged. This effect is depicted in **Figure 2-24** for certain aircraft fuels.

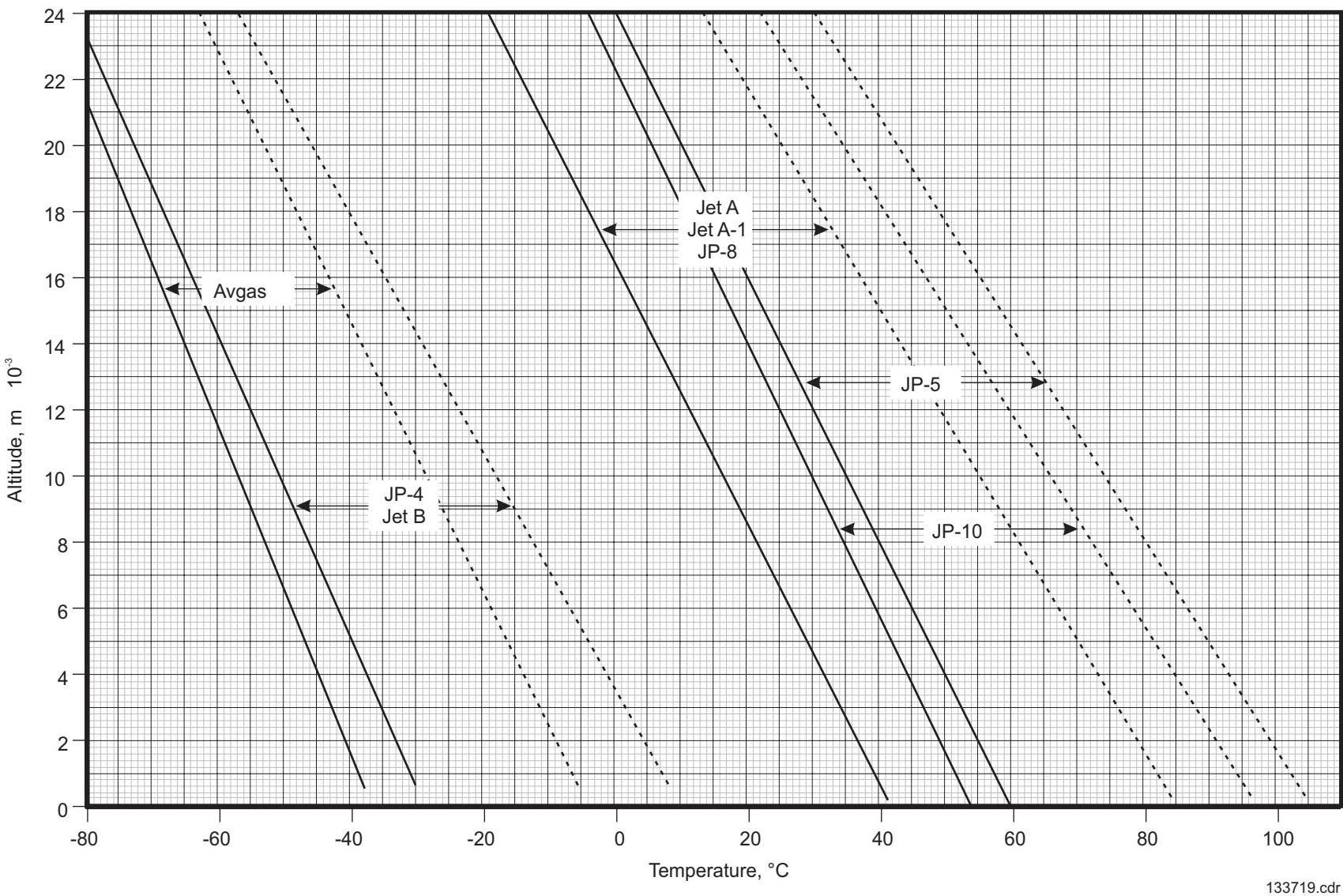


Figure 2-22. Fuels Flammability Limits Versus Altitude

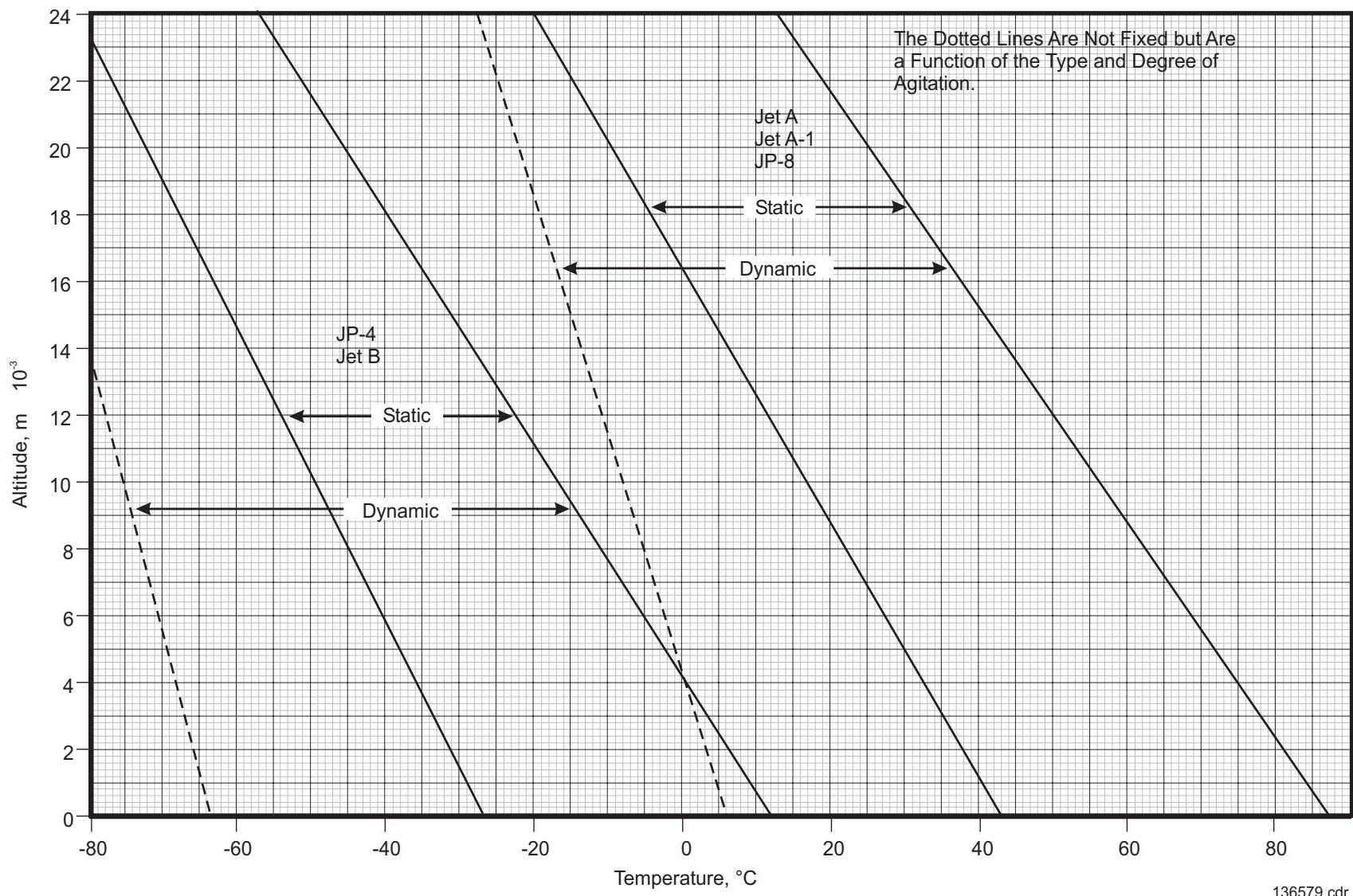


Figure 2-23. Dynamic Effects on Flammability Limits

2.8.6 Minimum Spark Ignition Energy of Fuels

Under ideal conditions (glass-flanged metal electrodes with a gap of about 0.4 cm), the minimum amount of energy required for a spark discharge to ignite an optimum hydrocarbon fuel/air mixture is in the 0.20 to 1 mJ range. The optimum fuel/air mixture is normally found at a point on the rich side near the stoichiometric point. As conditions depart from an ideal state, the energy requirements increase. Changing the fuel/air mixture, the electrode geometry, or the gap distance will increase the amount of energy required for ignition. If the fuel is present in the form of a mist or spray, as opposed to a vapor, the ignition energy requirements will increase. On the other hand, an increase in the oxygen concentration of the air, such as found in aircraft ullage at altitude, will decrease the amount of energy required for ignition.

The minimum ignition energy for sprays of aircraft fuels are given in *Figure 2-25*. The spark ignition energy required to ignite a spray of fuel varies with the temperature and is dependent upon the volatility of the fuel in question. Other variables include the configuration of the nozzle delivering the spray and pressure on the fuel which determines the droplet sizes in the spray.

These data, therefore, should not be taken as absolute for all spray devices, and are only presented to give relative values. Laboratory data with premixed air spray mixtures give much lower ignition energy values, but are still in the same relative order and spread. The data for Jet B and Jet A were determined experimentally with the balance estimated from flash point data. With the exception of Jet B/JP-4, all aircraft fuels covered generally have the same ignition level requirements. *Figure 2-26* presents estimates based on flash point data for JP-10.

2.8.7 Spontaneous Ignition

As a fuel is heated in air, the corresponding rate of oxidation and heat release will increase. If the heat is not removed, the fuel can reach a temperature where it will spontaneously ignite without the presence of an ignition source such as a flame or spark. Examples of phenomena involving spontaneous ignition include the combustion of oily rags stored tightly packed in a drum and the combustion of fuel in a diesel engine cylinder during compressive heating.

Spontaneous ignition tests involve measuring the temperature at which a fuel will first ignite without an ignition source. There are two general types of spontaneous ignition temperature measurements. Autoignition temperature (AIT) measures the point at which fuel vapors will first ignite in a glass flask without a flame or a spark. ASTM E 659 is an autoignition temperature test which uses a 500 mL round bottom flask heated in a furnace to a predetermined temperature and fuel injected. Autoignition is evidenced by the sudden appearance of a flame inside the flask and a sharp rise in the temperature of the gas mixture. The lowest internal flask temperature at which ignition occurs is defined as the AIT. Thus, the AIT is essentially the lowest temperature at which a fuel will ignite spontaneously in air at atmospheric pressure.

The detailed composition of the fuel can influence AIT. For example, aromatics have much higher AITs than normal paraffins with the same carbon number, and normal paraffins generally show a decreasing AIT with increasing carbon number. Because of these compositional effects, more volatile aromatic motor gasoline will generally have a higher AIT than will less volatile, lower aromatic kerosine-based turbine fuels.

Hot surface ignition test (HSIT), a second type of spontaneous ignition test, involves impinging the fuel onto a heated surface until ignition occurs. In compliance with Federal Test Standard 791C Method 6051, the fuel is dripped onto the surface of an internally heated 3-in. manifold until ignition occurs. There is no unique threshold temperature for HSIT tests because they are influenced by a number of variables such as geometry, closed versus open tests, air flow velocity, and residence time. For hydrocarbon fuels, autoignition tests show AITs ranging from 400° to 500°F, whereas hot surface ignition type tests show higher HSIT temperatures of 800° to 1200°F.

Consideration must be given to safety issues involving all of the parameters involved including fuel temperature, pressure, flow velocity, size or length of hot surfaces, obstructions and insulation effects during the design process. Detailed discussions of some safety design methodologies are contained in *Reference 10* and *Reference 22*.

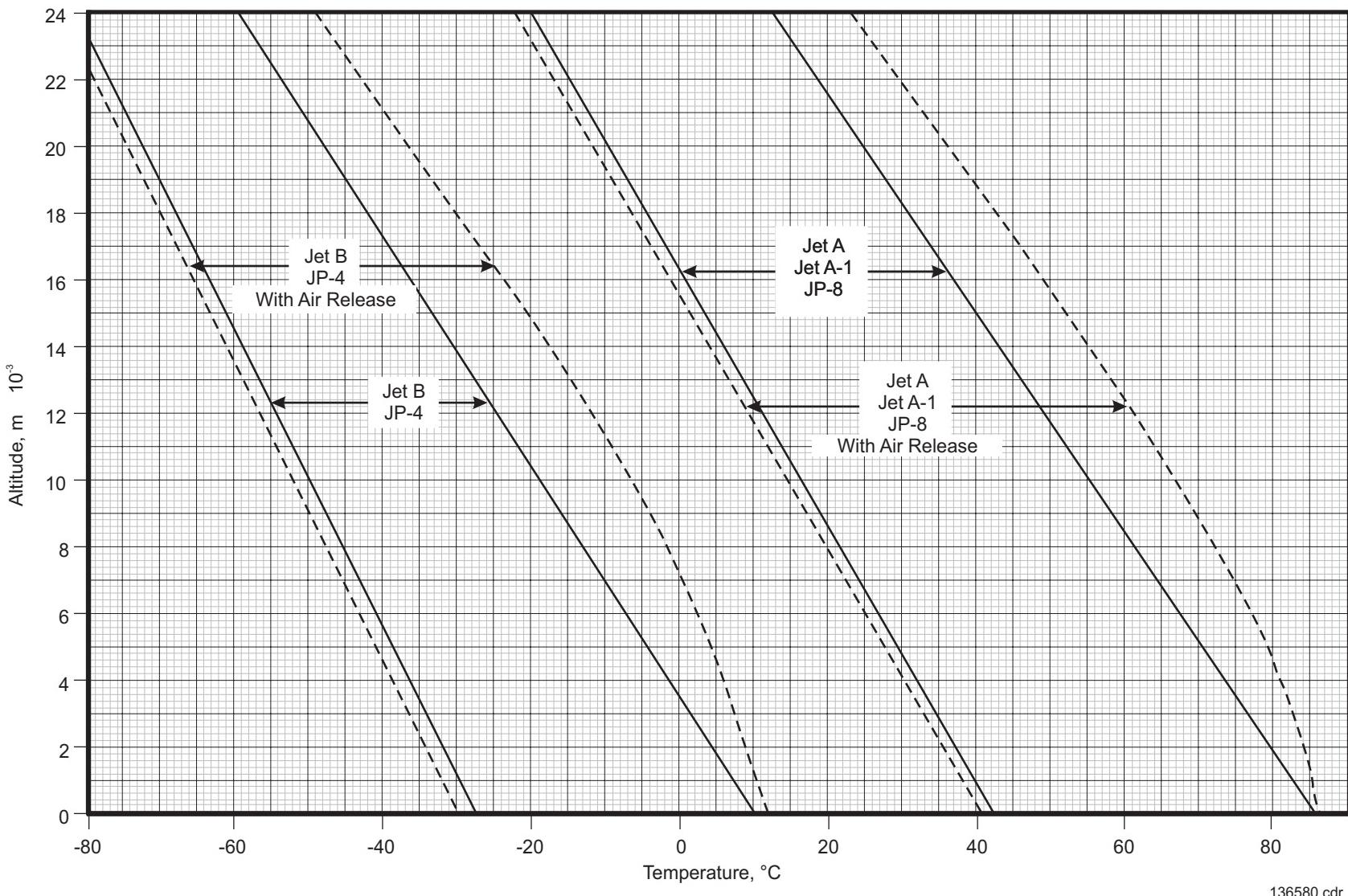
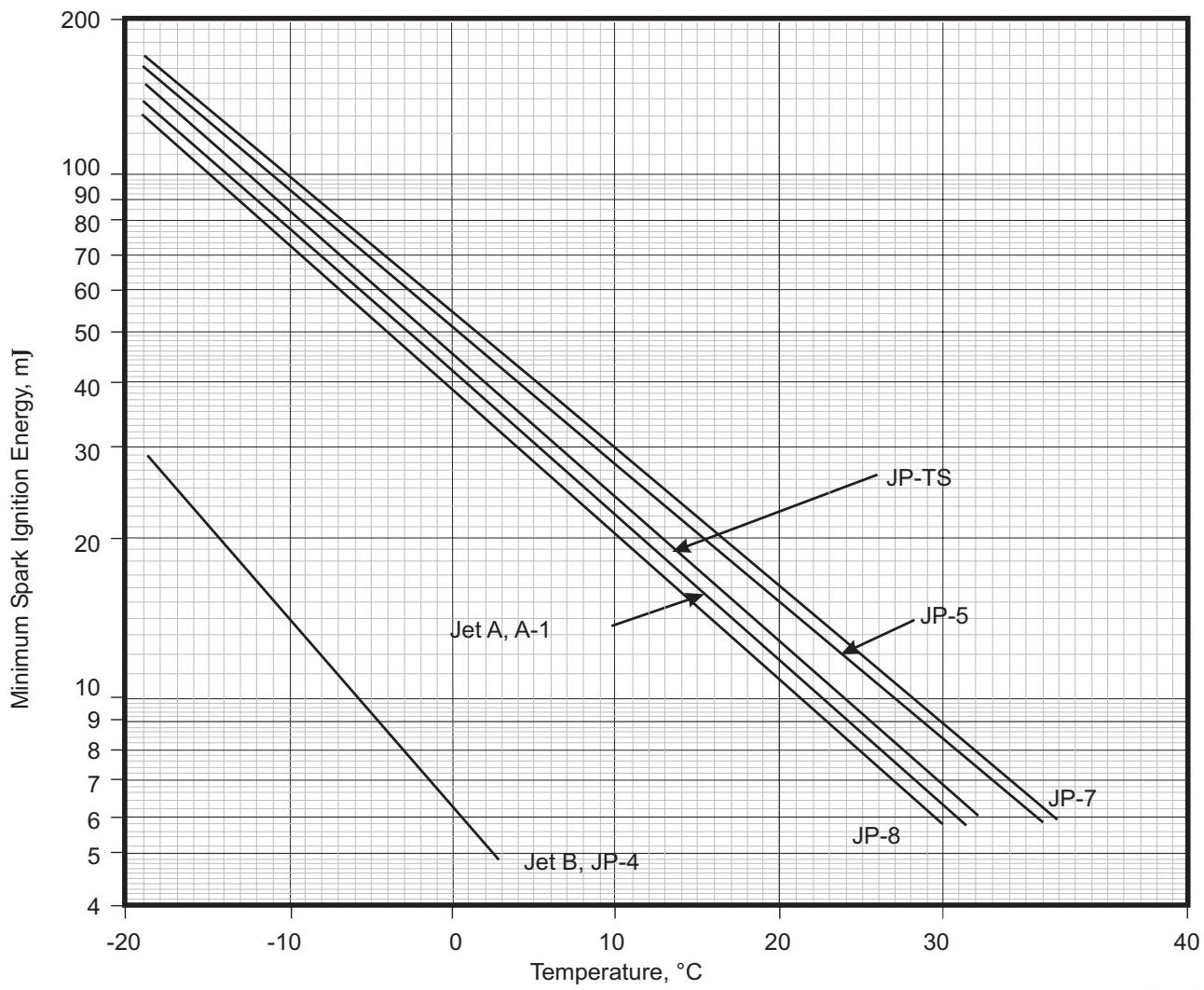


Figure 2-24. Effect of Air Release on Flammability Limits



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Figure 2-25. Minimum Spark Ignition Energy at 1 atm for Fuel Sprays

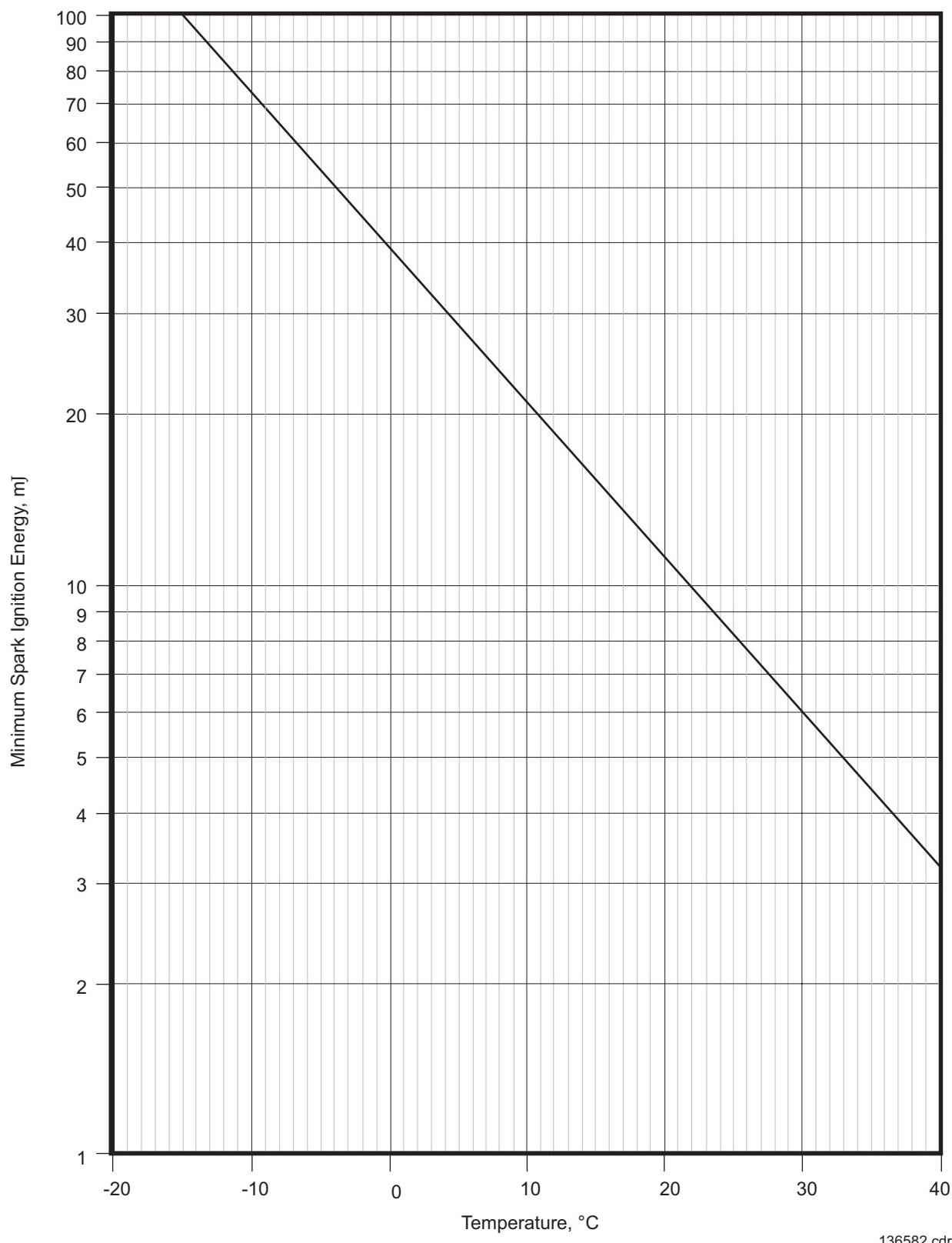


Figure 2-26. Minimum Spark Ignition Energy at 1 atm for JP-10 Sprays

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2.9 BULK MODULUS

The compressibility of a fluid is the decrease in the volume of a fixed amount of fluid when pressure is applied to that fluid. The measure of this compressibility is called the bulk modulus of the fluid and is defined by the differential equation

$$\text{Bulk Modulus} = -v(dp/dv)$$

Bulk modulus measures unit force per unit area. A fluid with a high bulk modulus shows a small change in volume for a given change in pressure and is, therefore, difficult to compress. Applying this principle, a fuel used to activate hydraulic equipment should have a high bulk modulus of the fuel to make a responsive system.

There are two kinds of bulk moduli. The first, called the isothermal bulk modulus, manifests at constant temperature and is used when a relatively slow compression process takes place. Adiabatic bulk modulus is the second type and occurs where sudden changes in pressure are exerted on the fuel. It is used in calculating reaction speeds of servomechanisms and the forces acting on pump components. The isothermal and adiabatic bulk moduli are related through the expression: $BS/BT = Cp/Cv$ which is approximately equal to 1.15 for jet fuel where BS equals adiabatic bulk modulus and BT equals isothermal bulk modulus.

Bulk moduli can be calculated from P–V–T measurements or determined directly from ultrasonic velocity measurements. The P–V–T measurements method is used primarily in isothermal conditions. Since it uses actual measured quantities rather than their derivatives, the ultrasonic velocity method is more accurate and yields the adiabatic bulk modulus directly. **Figures 2-27 and 2-28** show the adiabatic bulk moduli for JP-4, Jet B, JP-5, Jet A, Jet A-1, and JP-8 versus pressure and temperature.

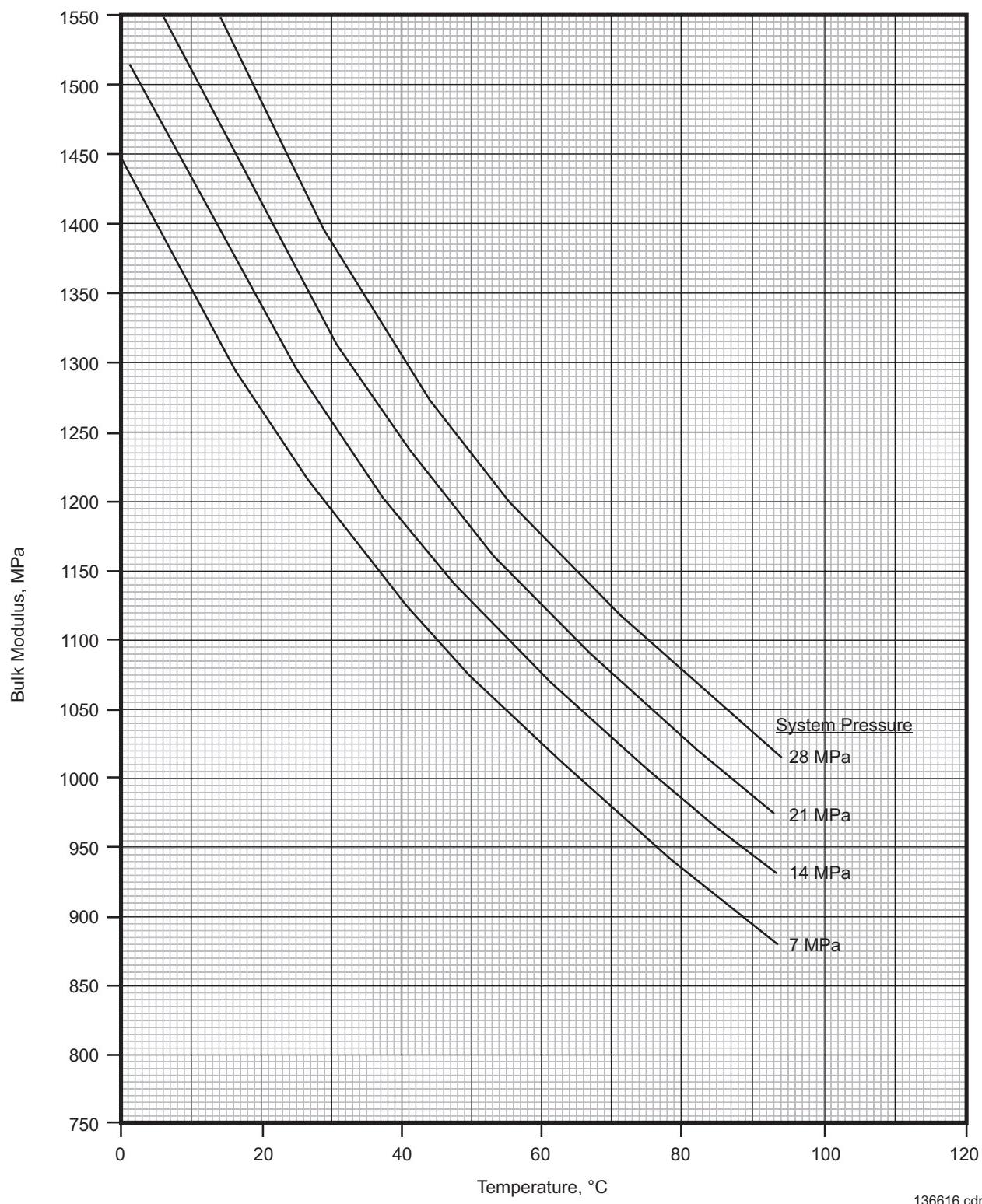
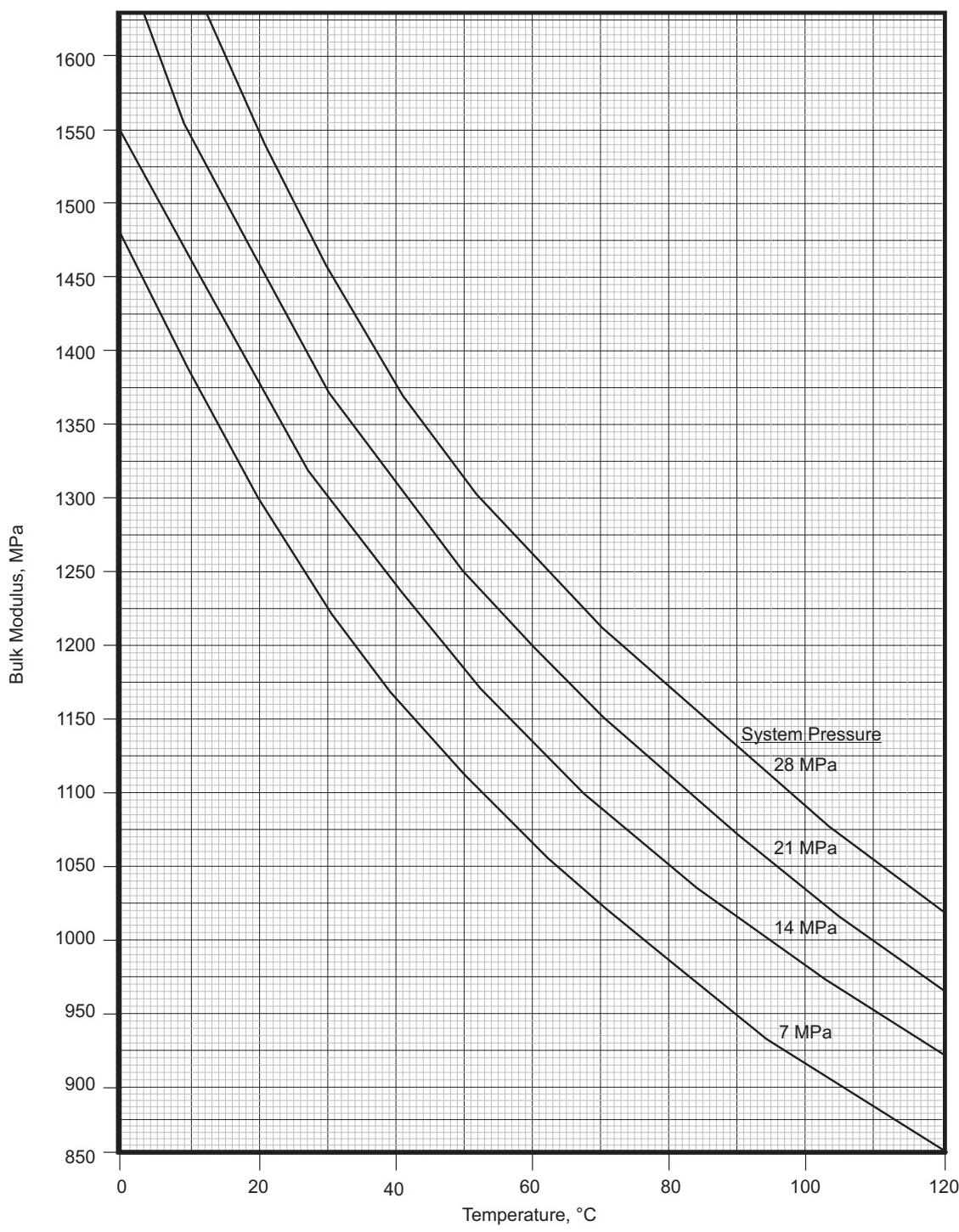


Figure 2-27. Bulk Modulus Versus Temperature and Pressure for Typical JP-4/Jet B

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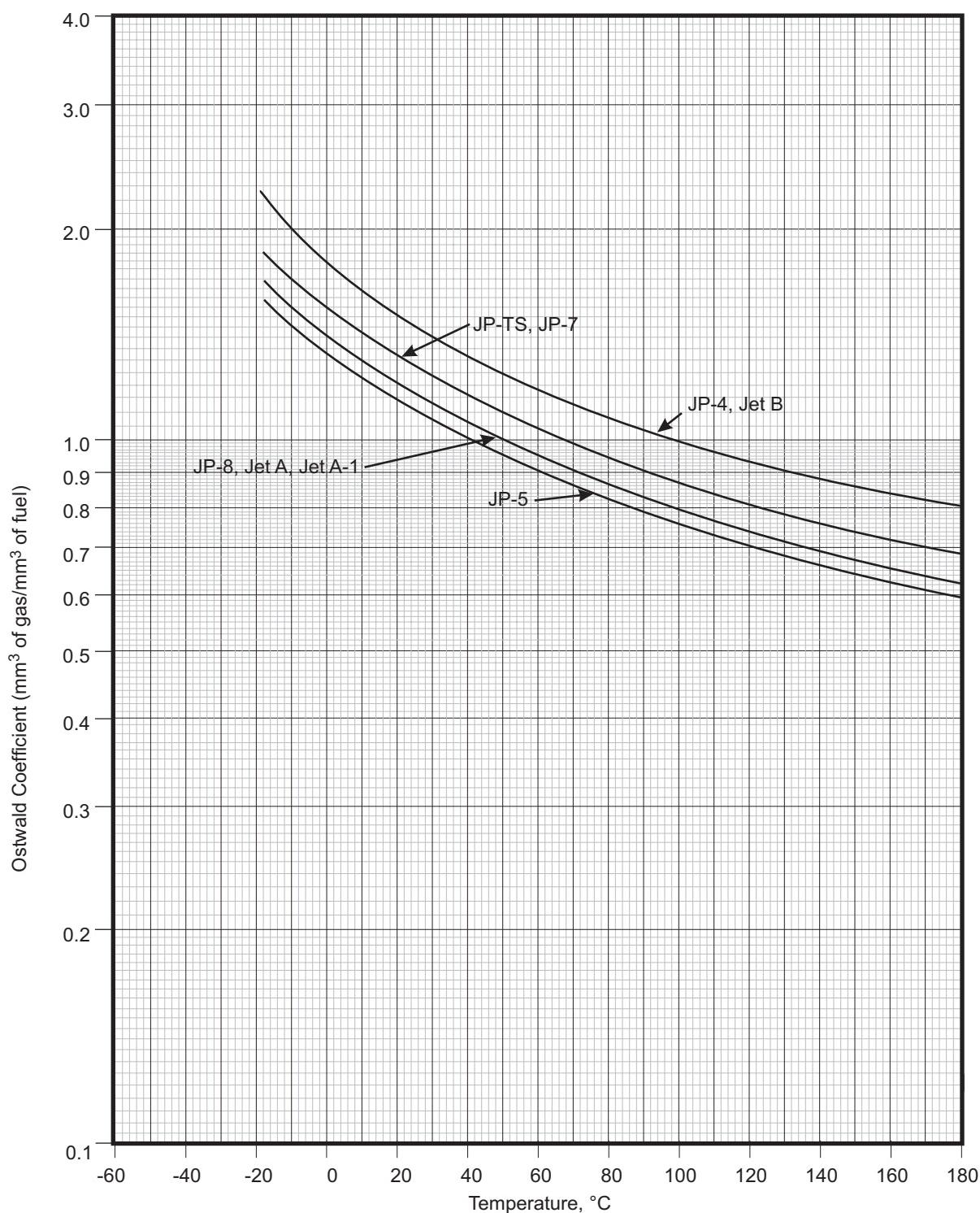


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Figure 2-28. Bulk Modulus Versus Temperature and Pressure for Typical JP-5, Jet A, Jet A-1, and JP-8

2.10 SOLUBILITY OF GASES

The solubility of gases in fuels is of high importance to the proper design of fuel systems and their components. High evolution of gases during climb can cause decreased pressure resulting in loss of fuel and, when pumping fuel, gas phase separation can occur leading to vapor lock or cavitation problems. The Ostwald Coefficient is the volume of gas dissolved in one volume of solvent. While several variables affect the solubility of gases in fuels including temperature, pressure, nature of fuel, and the gas itself, Ostwald Coefficient is independent of pressure, and the gas volume is measured at the conditions of the solution. *Figures 2-29 and 2-30* give the typical solubility of CO₂, O₂, and N₂ in aviation fuels. *Figure 2-31* provides the typical solubility of air in JP-10. Carbon dioxide, unlike the other gases, decreases in solubility with increasing temperature. The solubility of this gas is very high.



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Figure 2-29. Solubility of CO₂ in Aviation Fuels

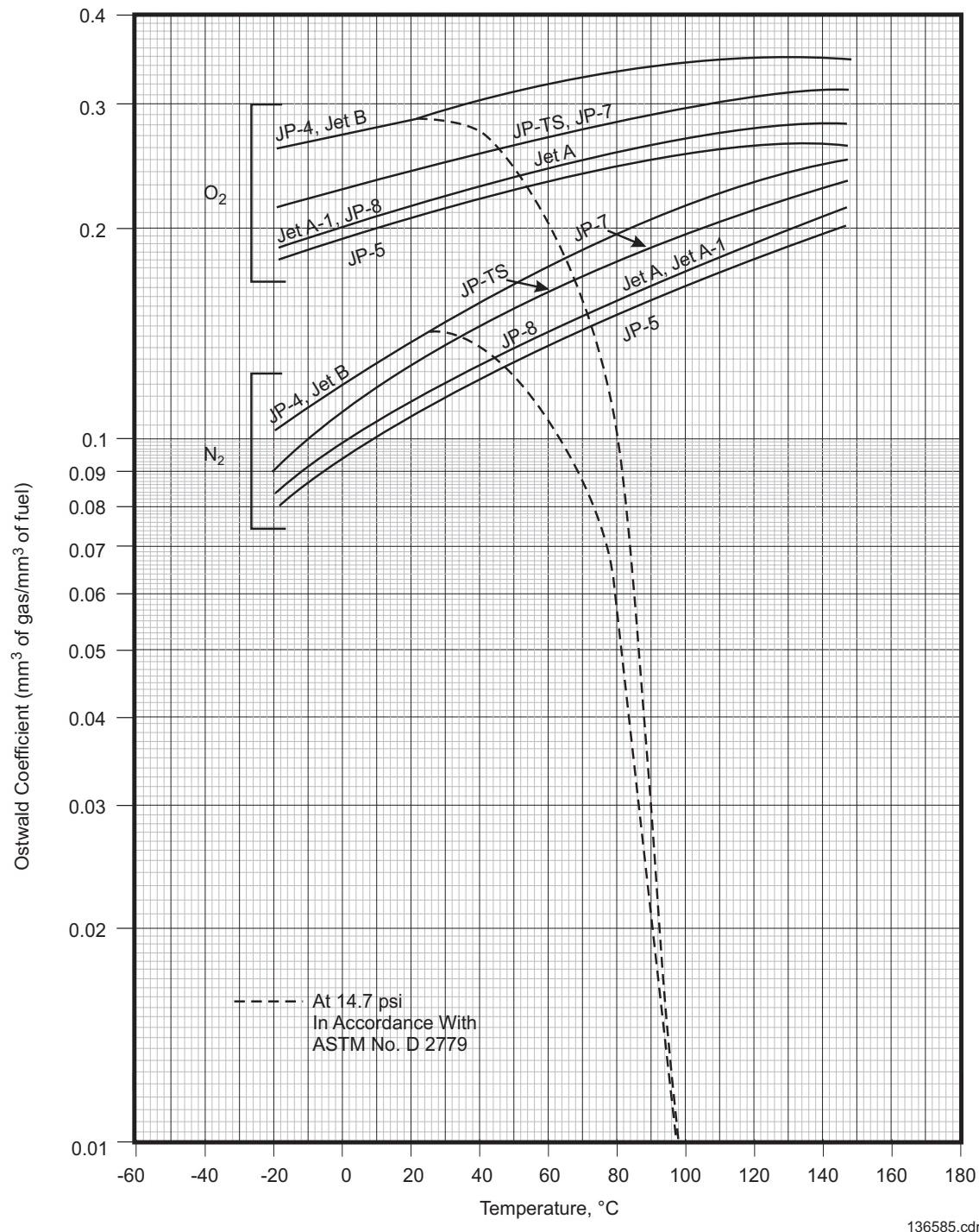


Figure 2-30. Solubility of O₂ and N₂ in Aviation Fuels

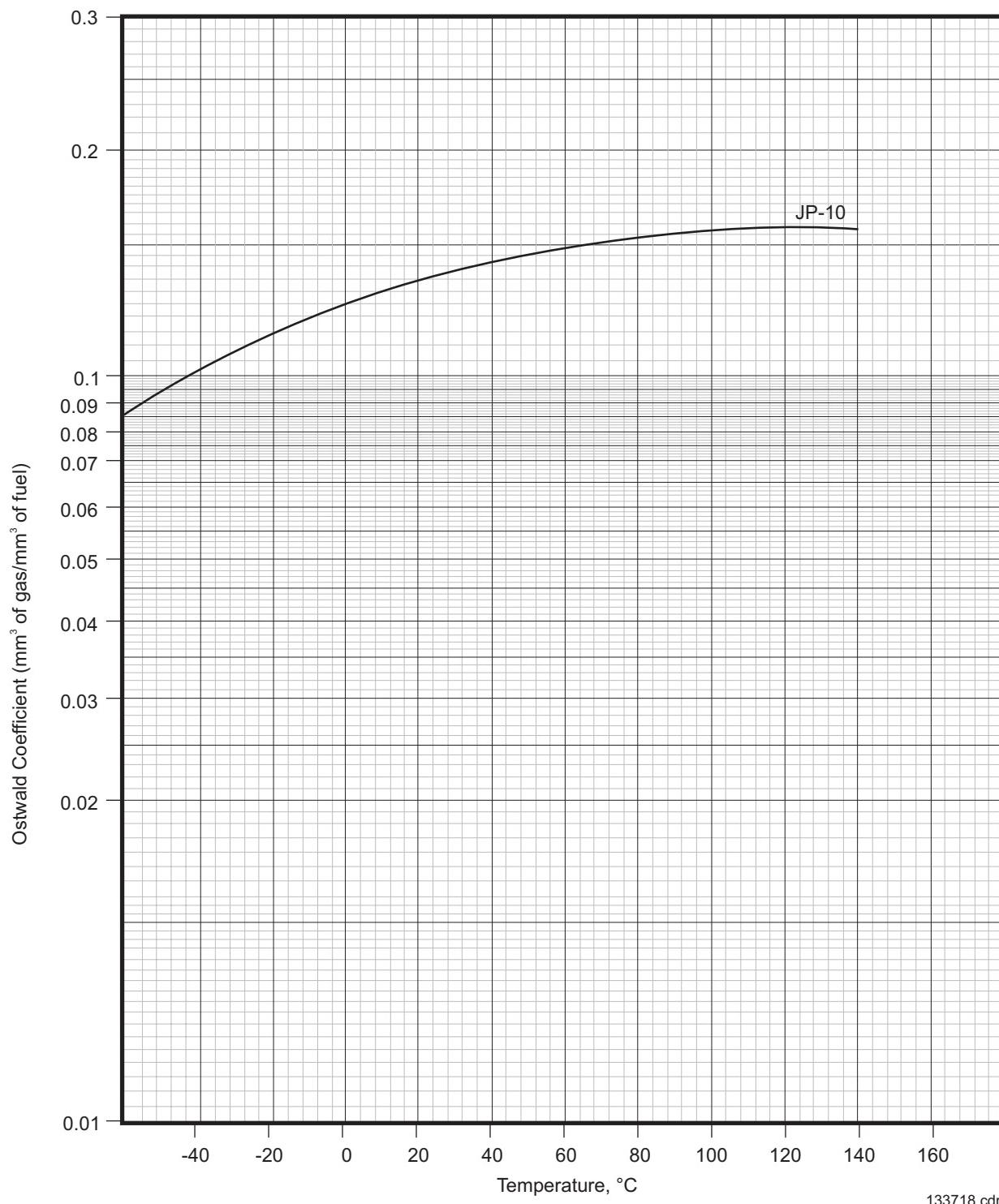


Figure 2-31. Solubility of Air in JP-10

2.11 SOLUBILITY OF WATER

The quantity of water dissolved in aircraft fuels is determined by the partial pressure of water in the vapor space above the fuel. When this vapor space is saturated with water at a given temperature, i.e., 100 percent relative humidity, the water dissolved in fuel at equilibrium will reflect the saturation values shown in *Figures 2-32* and *2-33*. At relative humidity values less than 100 percent, the amount of water dissolved in fuel will be correspondingly less than saturation values in accordance with Henry's Law.

Because water solubility is sensitive to temperature, a drop of 10°C in water-saturated fuel's temperature will create from 15 to 25 ppm of undissolved or "free water." It is difficult to visually detect "free water" at levels below 30 ppm. Several go/no-go tests, including the Shell Water Detector, can be used to detect levels in the range of 15 to 30 ppm. For quantitative measurement in the range of 1 to 60 ppm, ASTM D 3240 is frequently used.

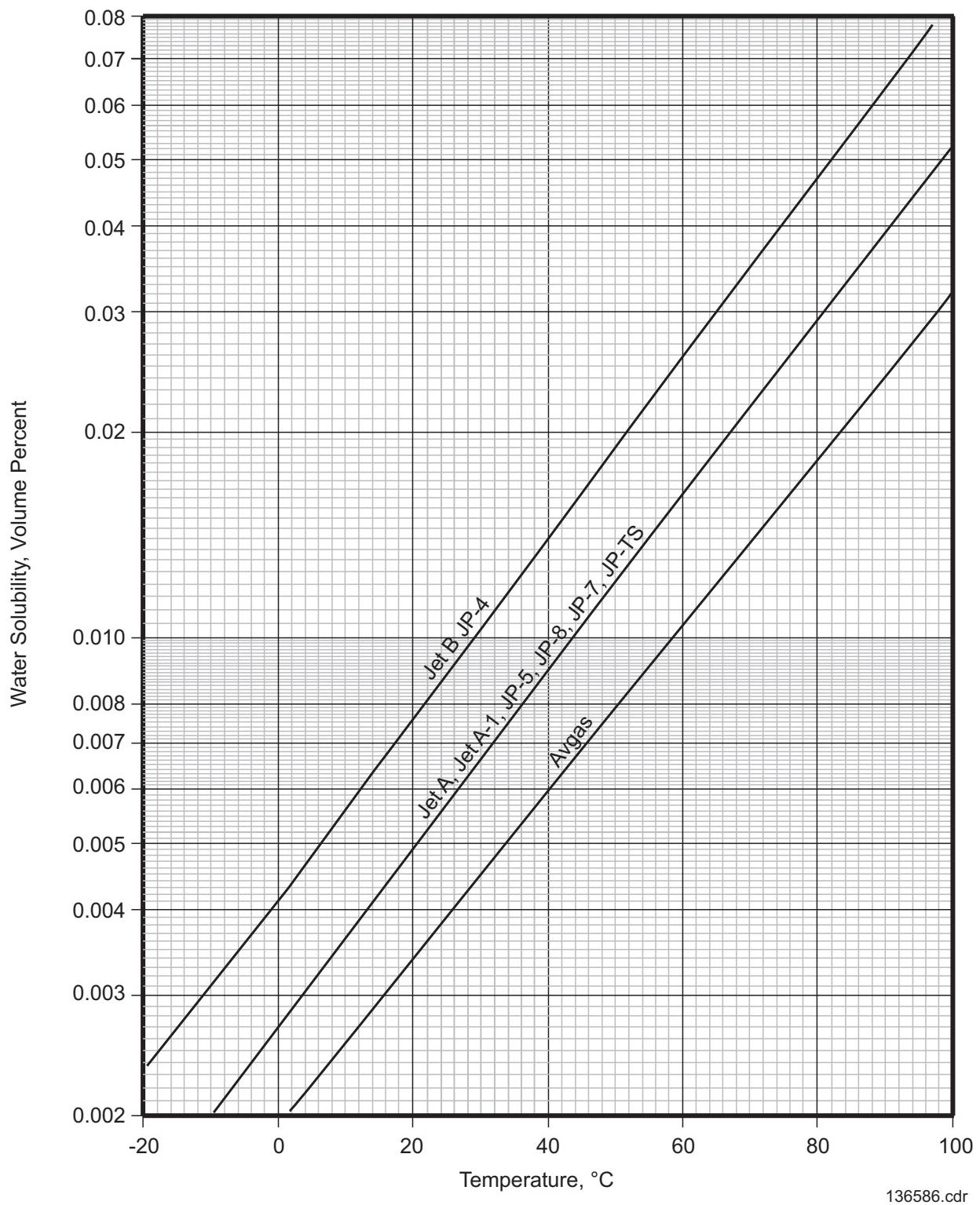
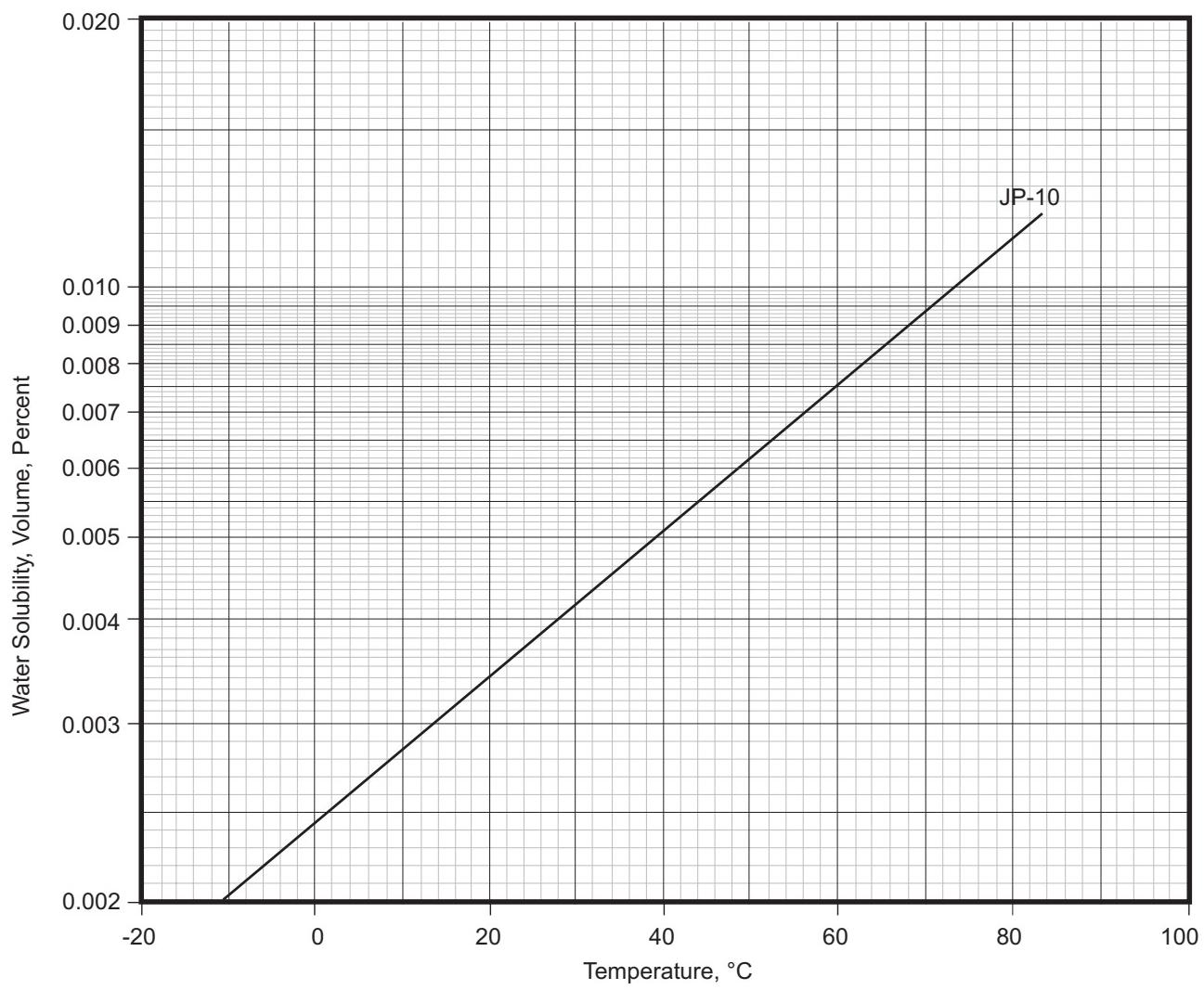


Figure 2-32. Water Solubility Versus Temperature for Aircraft Fuels

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Figure 2-33. *Water Solubility Versus Temperature for JP-10*

2.12 THERMAL OXIDATION STABILITY

The high-temperature stability of a fuel is its ability to resist oxidation at high temperatures that leads to undesirable degradation products such as sediments and/or surface deposits. Trace components including olefins, heteroatoms, and dissolved metals are found in fuels and play a significant role in this degradation process. Minimizing these contaminants is an effective method of improving stability. Lengthy, high-temperature exposure increases the thermal stresses on fuel and its tendency to form deposits.

Fuel stability has considerable impact on jet engine design and is of particular concern to the fuel system designer. Fuel is often used as a heat sink to cool the oil in an engine or to cool avionics and other equipment. Breakdown of the fuel can cause decreased heat transfer from the oil to the fuel resulting in degradation of the oil. In other parts of the engine system, deposits and gum formation can cause a reduction in performance.

2.12.1 Test Devices

The overall process leading to the formation of oxidative thermal stability sediments and surface deposits is complex reflecting factors such as the variety of crude sources and the differences in refining processes, as well as the various stress environments to which a jet fuel is exposed. Simple laboratory test procedures are, therefore, not applicable for predicting fuel stability, and extensive work has been done to develop complex tests that will predict this fuel characteristic. These devices range from laboratory static and flow test devices and larger scale flow devices to reduced scale fuel system simulators. The ASTM D 3241 JFTOT is widely used in specifications to determine if a jet fuel's thermal stability quality is sufficient to meet the requirements of aircraft and engine hardware. The JFTOT is a flow test in which 600 mL of air saturated fuel is passed for 2.5 hours through a heated test section containing a specially designed tube and then through a test filter. The level of surface deposits on the tube is rated visually and the pressure buildup across the filter is measured.

2.12.2 Effect of Deoxygenation

When in equilibrium with air at atmospheric pressure and at room temperature, jet fuel will normally contain fifty to sixty ppm of dissolved oxygen. Complex free radical reactions that result in sediment and surface deposit formation require dissolved molecular oxygen in the storage and thermal stability temperature ranges. Removing dissolved molecular oxygen could, therefore, improve the stability of fuels. Many studies have been conducted to explore the effect of deoxygenation on deposit formation and, in general, the removal of air from a fuel does markedly reduce deposit formation. Two deposit formation processes occur at different temperature ranges. The first is a lower temperature deposit formation process involving molecular oxygen while the second, a higher temperature pyrolysis process, is independent of oxygen. With stable hydrocarbons, deoxygenation greatly reduces low-temperature liquid phase deposit formation rates, and significant rates of deposit formation do not occur until higher temperatures are applied.

2.12.3 Effect of Soluble Metals on Deposit Formation

Soluble metals are believed to be present in fuels in the form of acid salts or organic complexes. They are picked up by the reaction of the fuels with certain metal surfaces during transit. Some metals are highly reactive to fuels and are a source of soluble metals. Copper, zinc, lead, and cadmium will react with naphthenic acids in fuels to form acid salts (*Reference 15*). **Table 2-6** is an example of the degradation of fuel stability due to different soluble metals, namely copper, iron, and zinc. The breakpoint of each of the six JP-5 fuels is shown before the addition of any metal. The amount of each separate metal required to degrade a particular fuel to the breakpoint level of 260°C is then recorded. Note that some fuels are significantly more sensitive to metals than the fuels shown in Table 2-6. Using this process, it has been determined that copper is the most detrimental of these three soluble metals because it required the least amount of metal addition to reduce the breakpoint to 260°C. Iron follows copper in activity, with zinc requiring the most additional metal to reach the same breakpoint level.

Table 2-6. Effects of Metal Concentration on Thermal Stability

Fuel	Breakpoint Temperature °C Before Metal Addition	Concentration Required to Degrade Breakpoint to 260°C (ppb soluble metal)			
		Copper	or	Iron	or
		Zinc			
A	271	74		136	
B	268	99		165	
C	282	105		154	250
D	279	89		151	200
E	282	50		145	250
F	296	100		152	420

Determined by ASTM D 3241 JFTOT

2.12.4 Effect of Metal Surfaces on Thermal Stability

That certain metal surfaces have been found to catalyze the degradation of fuels is very important in the design of aircraft fuel systems, particularly where high temperatures are encountered as in heat exchangers. This characteristic makes copper and its alloys, such as brass, the least appealing of the metals. Other metals and alloys such as titanium vanadium alloys, beryllium, lead, tungsten, tungsten alloys, zinc, nickel, silver, L-605 alloy, 1015 steel, and 304 stainless steel were found to decrease fuel stability. Metals and metal alloys that had little or no affect on fuel stability included 446 stainless steel, 6061 aluminum, nickel 200, 316 stainless steel, Inconel 600, and Hastelloy C. Additional information is found in **Reference 15**.

2.12.5 Effect of Fuel Additives on Oxidative Stability

In general, the thermal stability of fuels should be satisfactory as produced, without the use of additives. If allowed to form, peroxides can degrade thermal stability quality or result in elastomer attack however, antioxidants prevent the formation of peroxides in fuels during storage. Antioxidants are generally added only to fuels that have been hydrotreated, a process that can remove naturally present antioxidants, or to fuels that may be stored for very long periods of time with the potential for the exhaustion of naturally occurring antioxidants. Metal deactivator additive can chelate dissolved metals like copper, and thus is added to fuel to prevent any metals present from catalyzing oxidative stability reactions and causing degradation. The U.S. Air Force has developed and uses a thermal stability additive to raise the thermal stability limit of a fuel such as JP-8 by 100°F. Designated JP-8+100, the additive treated fuel contains a strong dispersant/detergent additive that requires special handling precautions. The JP-8+100 additive has been shown to produce 50 to 95 percent reductions in deposits in a wide variety of thermal stability test rigs with a wide variety of JP-8/Jet A fuels. Several base-level trials have quantified significant reductions in fuel-related engine maintenance during use of the additive.

2.13 AROMATICS

In turbine fuels, aromatics have less desirable combustion characteristics than paraffins or cycloparaffins, and are limited by specifications. Typical aromatic levels of various turbine fuels are shown in *Table 2-7*.

Table 2-7. Typical Aromatic and Total Sulfur Levels of Fuels

	<i>Aromatics, Volume %</i>	<i>Total Sulfur, Weight %</i>
Jet A	18.1	0.068
Jet A-1	18.0	0.046
JP-8 (U.S.)	17.3	0.049
JP-5	19.1	0.047
JP-7	1.5	0
JP-TS	9.9	0.026
JP-4	8.1	0.046
Avgas Grade100LL	NA	0.005

2.14 TOTAL SULFUR

In addition to hydrocarbons, turbine fuels have low levels of sulfur containing heteroatom compounds. All specifications limit the total sulfur level of fuels because of concerns regarding the effect of sulfur oxides formed during the combustion process. Typical total sulfur levels of various turbine fuels are shown in *Table 2-7*.

2.15 SPECIALTY FUELS PF-1 AND RP-1

Typical properties of PF-1 and RP-1 are shown in *Table 2-8*.

Table 2-8. Typical Properties of PF-1 and RP-1

	<i>PF-1</i>	<i>RP-1</i>
Relative Density 15.5/15.5	0.916	0.804
Distillation °C		
IBP	188	
T10	197	
T50	205	
T90	219	
End Point	236	
Viscosity at -54°C cSt	23.4	
Flash Point °C	25	68
Freezing Point °C	-58	<-37
Heat of Combustion MJ/kg	42.3	43.3

2.16 CALIBRATING FLUID MIL-PRF-7024 TYPE II

Calibration fluid specifications and typical properties are shown in *Table 2-9*.

Table 2-9. Calibrating Fluid Mil-PRF-7024 Type II Typical Properties

	<i>Specification</i>	<i>Typical Properties</i>
Specific Gravity at 60°F	0.765 to 0.775	0.768
Flash Point, °C (°F)	38 (100) Min	42 (107)
Viscosity at 25°F, cSt	1.12 - 1.22	1.18
Aromatics, Volume %	20 Max	<1.0
Olefins, Volume %	5 Max	<1.0
Benzene, Volume %	0.01 Max	<0.01
Existent Gum, mg/100 mL	5 Max	<0.5
Particulate Matter, mg/L	2.0 Max	1.3
TAN, mg KOH/g	0.015 Max	0.009
Distillation °C (°F)		
Initial Boiling Point	149 (300) Min	161 (321)
Final Point	210 (410) Max	179 (355)
% Recovered	98.5 Min	99.0

2.17 PROPERTY DATA AND VARIABILITY

2.17.1 Property Data Sources

The property data contained in this Handbook was generally developed by one of two methods. The first approach involved the use of specification test results. Properties cited in specifications are measured as a matter of course, and many of these results are collected and tabulated in extensive surveys, such as those conducted by the DESC (*Reference 35*) and the UK Ministry of Defence (MOD) (*Reference 41*) on an annual basis for JP-8, principally produced in the U.S. (JP-8 U.S.), JP-5, JP-4 and Jet A-1. The API has also recently reported on an extensive survey of some Jet A properties (*Reference 20*). The DESC and MOD surveys report volumetrically averaged results and also report the data variability by calculating the standard deviation of reported results around the calculated mean. Extensive flash point data was also reported recently by the Fuel Tank Harmonization Working Group (FTHWG) (*Reference 36*). The U.S. Air Force San Antonio Air Logistics Center provided extensive data on specialty fuels such as JP-7 and JP-TS.

In addition to data obtained from large survey databases, data was also used that was obtained from smaller data sets supplied by the Annual National Institute of Petroleum and Energy Research (NIPER, formerly Bureau of Mines) and other sources (*Reference 17*). These data were used to provide values otherwise not available from the larger surveys. No survey data was available for aviation gasoline, however typical production property values for Avgas grade 100LL were supplied by a number of North American and European producers, and the results simply averaged.

The specification data provided well established average results at the conditions stipulated by the specification, e.g. temperature. Where required in data plots, these results were extrapolated to other temperatures. The effects of temperature on the various properties were investigated resulting in the corroboration or modification of existing temperature effects data. Non-specification derived properties, or properties not routinely required to be measured to demonstrate conformance to a specification, were individually investigated to either corroborate the existing data or to modify the values based on newer or more reliable data. In general, non-specification property values are derived from much smaller data bases and there is little, if any, data available on property variability.

2.17.2 Property Variability

Property variability data is shown in **Table 2-10**. Values for Jet A-1 were obtained from the MOD survey, values for JP-8 (U.S.) and JP-5 were obtained from the DESC survey, and the FTHWG report provides the standard deviation for Jet A flash point. The standard deviations for the standard test method (STM) are shown as are the total variability values, i.e. the standard deviation for the values reported around the mean property value. The standard deviations for the STMs were calculated by dividing the STM reproducibility by 2.77. This factor was obtained from ASTM D 6300, and is the value for infinite degrees of freedom.

Table 2-10. Variability of Properties

	<i>Jet A</i>	<i>Jet A-1</i>	<i>JP-8 (U.S.)</i>	<i>JP-5</i>
Density at 15°C kg/m ³				
Average Density	810	802	806	813
Standard Deviation of Test Method (ASTM D 1298)	0.43	0.43	0.43	0.43
Standard Deviation of Density	NA	6.47	NA	NA
Relative Density at 15.5/15.5°C				
Average Relative Density				
Unitless	0.811	0.803	0.807	0.814
°API			43.9	42.3
Standard Deviation of Test Method				
Unitless	0.00043	0.00043	0.00043	0.00043
°API			0.1	0.1
Standard Deviation of Relative Density	NA	NA	2.7 °API	2.6 °API
Flash Point, °C				
Average Flash Point	51.2	42.2	48.9	63.3
Standard Deviation of Test Method (ASTM D 56)	1.6		1.6	1.6
Standard Deviation of Flash Point	5.8	2.5	5.9	2.0
Aromatics, Volume %				
Average Aromatics	18.1	18.0	17.3	19.1
Standard Deviation of Test Method	0.96	0.96	0.95	0.97
Standard Deviation of Aromatics	NA	2.24	3.1	2.9
Total Sulfur, Weight %				
Average Total Sulfur	0.068	0.046	0.049	0.047
Standard Deviation of Test Method	0.004	0.004	0.004	0.004
Standard Deviation of Total Sulfur	NA	0.045	0.05	0.039

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3. FUELS AND DISTRIBUTION SYSTEM ISSUES

3.1 CONTAMINATION

Contaminants are virtually ubiquitous and can find their way into aviation fuels at many points in the distribution system. The most common contaminants are water, solids (as particulates), and microbial growth (at the fuel/ water interface). There are also items of contamination that can occur in a multi-product pipeline creating side issues to the above including the presence of surfactants, overdosing of additives, and mixing fuels.

3.1.1 Water Contamination

Dissolved Water

As shown in *Figures 2-32* and *2-33*, the solubility of water is dependent upon both temperature and fuel-type. Dissolved water is a normal component of fuel and is not considered a contaminant.

Excess or Free Water

Undissolved (free) water may be suspended in the fuel or settled at the bottom of storage or aircraft fuel tanks, or at the low points in the piping. Undissolved water is a fuel contaminant which can starve engines if injected as a slug into the engine system. It can also freeze to form ice crystals capable of plugging fuel filters and can support microbiological contamination, contributing to the corrosion of metallic components.

Water Separation

Because water does not fall out of kerosine-type fuels as readily as from gasoline or wide-cut fuels, it takes longer to remove free water by settling (*Figure 3-1*). The filtration equipment described in *Section 3.2.6* can, however, accelerate this process. Dissolved water is not removed by standard filtration equipment.

Means of Water Contamination

Free water can enter the fuel in several ways. Dissolved water in the fuel can come out of solution as the fuel cools due to diurnal cycles or during operation as the aircraft climbs to altitude, causing the water solubility in the fuel to decrease by roughly 1 ppm (volume) per °F. For example, if the dissolved water concentration is at the saturation level per *Figure 2-32*, cooling 10,000 gallons of turbine fuel from 60° to 10°F could create about a half gallon of free water.

A second source of water contamination is the condensation of atmospheric moisture. Condensation occurs when moisture laden air is drawn into the fuel tanks as fuel is consumed, and the air comes in contact with the cold fuel and tank surfaces at the end of a long flight. Floating roof tank seals that leak or fuel tank covers and caps that are left open during rains or aircraft washing are a third source of water contamination.

3.1.2 Water Prevention

The industry uses both hardware and quality control procedures (*housekeeping*) to defend against water contamination.

Hardware

Good engineering design practice requires fuel delivery systems have a minimum number of low points which are equipped with drains. Floating roof tanks should have a solid cover over the floating roof. All storage tanks should have drains reaching to the lowest point in the tank. Ice crystals are prevented from plugging filters in aircraft either by heating the filter, heating the fuel near the filter, or using FSII additive (*Section 1.1.3*). Aviation operation in periodically cold or continually cold climates introduce a set of problems caused by frozen water bottoms that cannot be drained. The industry has developed equipment and procedures to mitigate these problems, but challenges remain.

Filtration equipment is described in *Section 3.2.6*.

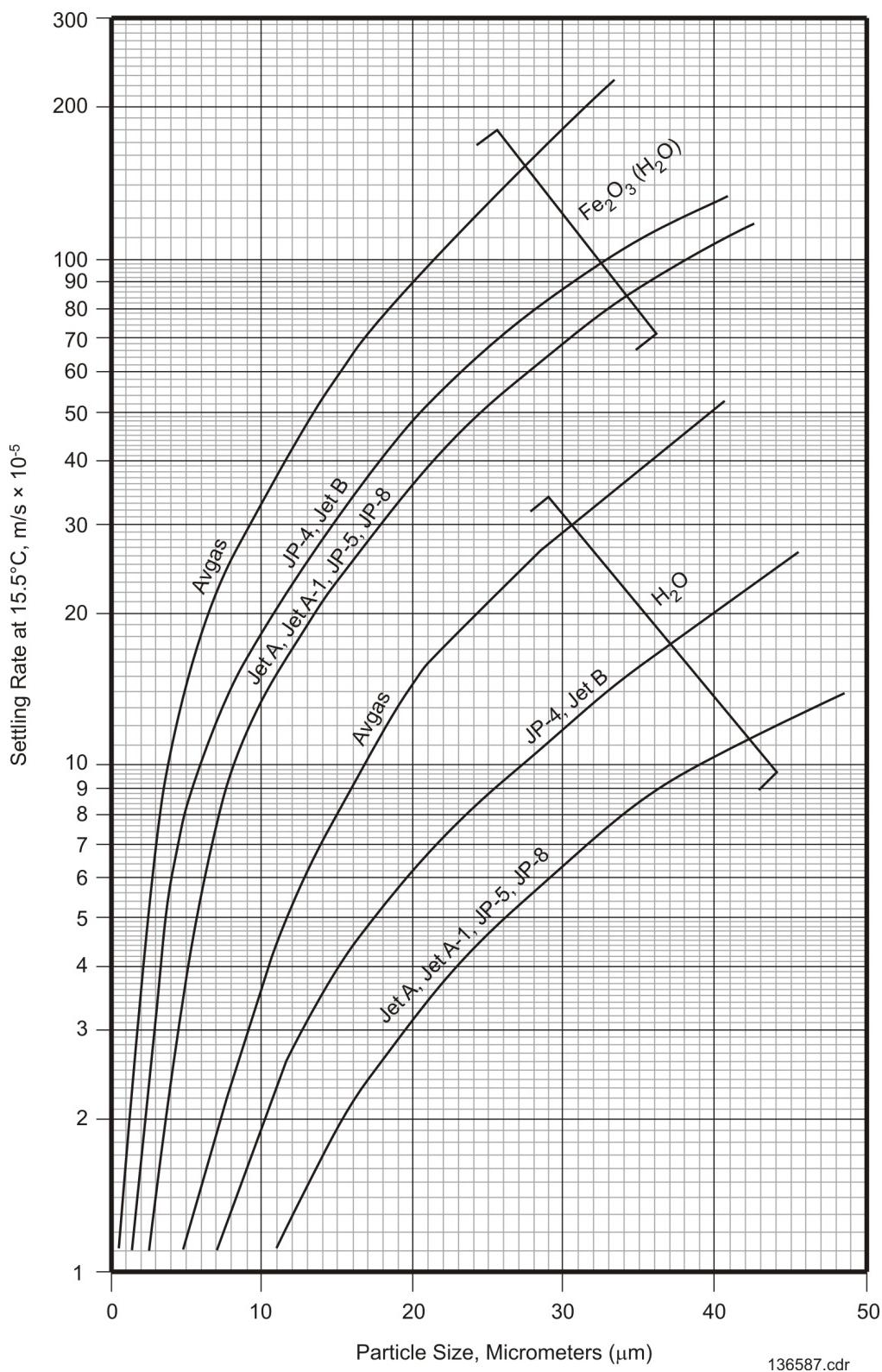


Figure 3-1. Separation of Contaminants — Water and Rust

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Quality Control Procedures

Good housekeeping includes regular programs of draining aircraft tank bottoms and fuel system low points to minimize the accumulation of free water, and monitoring the operation of filtration hardware. Airport quality control procedures, including those relevant to housekeeping issues, have been issued by the Air Transport Association (ATA) and the IATA.

3.1.3 Solid Contaminants

Solid contaminants most commonly found in fuel are rust, dirt, dust, and fibers. The rust generally comes from corrosion of distribution and handling system tanks and pipework. Dirt and dust originate from the ground and find their way into the fuel system through atmospheric vents and pipework left open for maintenance. Introduction of fibrous material can result from filter damage and degradation or aircraft maintenance work and can include forgotten cleaning rags, masks, gloves, lunch wrappings, etc. Semi-solid contaminants may result from microbial growth. Although microbes consist of 70 percent or more water, they can be filtered out and so are mentioned here.

Separation of Solids from Fuels

The primary methods for separating the solids from the fuel are settling and filtration. Settling is effective if the fuel can be retained in a holding or storage tank for an extended period. The rate of settling depends on the viscosity of the fuel and on the particle size, shape, and density (*Figure 3-1*). In the figure, note that the dirt, like water, does not settle as rapidly from kerosine-type fuels as it does from gasoline and wide-cut fuels. Normally the minimum accepted rate for settling turbine fuel in storage tanks is three hours per meter of fuel depth. Fuels processed through filters meeting aviation filtration specifications have solid content reduced to levels consistent with aircraft and engine requirements.

Effects of Particle Contamination

The presence of particulate matter can have several negative effects on engine hardware and operability. The main engine filters have a large pore size relative to fuel delivery filters, but internal fuel control filters can have pore sizes as small as 1.0 to 10.0 microns, absolute. When plugged, the filters go into bypass mode thereby exposing the control's moving parts to damaging particles that could limit control operation. If the aircraft fuel is sufficiently contaminated, the main engine filters could bypass leading to an aborted flight. Because solid contamination can abrade surfaces, it can also affect fuel nozzle flow divider seal life causing leaks and changing nozzle performance.

3.1.4 Solids Prevention

The primary protection against solid particles is sound fuel system design, proper filtration equipment, and good quality control procedures. Protective measures like filtration, pipeline and tank coatings, rust prevention linings, and floating suctions in storage tanks ensure that fuel is drawn off the top of the tank where it is cleanest, rather than from the tank bottom, where particulates and water accumulate. Good housekeeping consists of, but is not limited to, routine inspections of incoming product, current knowledge of maintenance actions, and post-action inspection of affected systems.

3.1.5 Microbial Contamination

Microbiological growth in storage, transport and aircraft fuel tanks can contaminate any fuel with solids (cell bodies) and biosurfactants. Problematic microbes such as fungi, bacteria, and yeasts live in the water at the fuel/water interface and metabolize (break down) fuel hydrocarbons, particularly straight-chain and sulfur-bearing compounds, enabling growth into slimes and mats. These growths can appear in a range of colors from black to green to red. ASTM D 6469 is recommended as a resource guide for microbiological growth in fuels.

Effects on Fuel systems

The growth of significant amounts of microbial life in storage and holding tanks can lead directly to solids and surfactant contamination. The same is true for aircraft fuel systems. Microbial growth has also been identified as the major cause of aircraft fuel capacitance probe fouling, causing fuel gages to read erroneously high. Acids produced by the microbes can contribute to the corrosion of metallic components including aircraft fuel tanks.

3.1.6 Microbial Prevention

All microbial growth is completely dependent on the presence of free water in the fuel. It is most effectively controlled by minimizing or eliminating free water in the fuel. (Dissolved water cannot be used by microbes.) If contamination does occur, there are effective biocides that are approved by engine manufacturers for the treatment of infestations. The biocide manufacturer should be consulted to determine the most effective course of treatment.

3.1.7 Dye Contamination

In many countries, government agencies require the addition of dyes to certain fuels. In the U.S., the Environmental Protection Agency (EPA) requires the addition of red dye to high sulfur distillate fuels, while the Internal Revenue Service (IRS) requires the addition of red dye to untaxed distillate fuels. Aircraft turbine fuels are specifically exempted from these dye requirements, but turbine fuels can become contaminated when they share a common element in the distribution system with the dyed fuel or otherwise come in contact with dyed fuel.

Major improvements in the operation of fungible multiproduct pipelines are minimizing the problem, but turbine fuel specifications ASTM D 1655, D 6615, and Def Stan 91-91 do not recognize dyes as approved additives, prohibiting the presence of unapproved additives such as dyes.

Effects of Dye Contamination

Research conducted at Southwest Research Institute and sponsored by a consortium of the U.S. Government, aviation original equipment manufacturer (OEM) companies, and the petroleum industry, indicates that the red dye mandated by the EPA/IRS can cause increased coking in hot parts of turbine engine fuel nozzles. At this writing, the research is not yet complete. The use of off-specification fuel can void engine and airframe warranties, but Emergency Use bulletins have been issued by most of the major engine, auxiliary power unit (APU), and airframe manufacturers to set limited use controls for dyed fuels found in hydrant systems to prevent airport shutdown. At this time, the program has shown that contamination by 0.0275 mg/L of red dye (0.025 percent of the minimum IRS concentration) is unacceptable. Planned future work may lead to the acceptance of a maximum allowable concentration of dye for continuous engine operation.

3.1.8 Dye Prevention

The best defense against dye contamination is continuous visual inspection of the fuel at points along the distribution system and at the point of delivery using the techniques outlined in ASTM Manual 5 and ATA Specification 103 for *White Bucket* testing or similar techniques.

3.1.9 Other Aviation Turbine Fuel Dyes

The U.S. Air Force has examined and approved a yellow leak detection dye for use in finding leaks in aircraft fuel tanks and delivery systems. Fuel containing this dye can be used for ground and flight operation when added to the fuel in concentrations not exceeding those specified in MIL-D-81298 (inactive for new designs), Type II Yellow. It is recommended that any equipment owner who wants to use this dye contact the relevant engine manufacturer for approval.

3.1.10 Surfactant Contamination

Surfactants are surface active materials that can enter turbine fuel as the result of inadequate processing, as the products of microbial contamination, by accidental inclusion, or by cross contamination in multi-product distribution systems. Surfactants can interfere with the removal of free water from the fuel by reducing water droplet size, resulting in longer than usual settling times and by rendering filter separators ineffective. Surfactants also disperse fine solids, preventing them from settling or from agglomerating in filter separators.

Minute levels of surfactants that occur naturally from the crude or the refinery processing are not considered contamination provided that water separation and filtration performance are acceptable.

Surfactant contamination in aviation fuels generally can be remedied through absorption by clay treatments. However, as will be seen in *Section 3.2.4*, the use of JP-8+100 in military systems raises surfactant problems to a much higher level.

3.2 OTHER TURBINE FUEL CONCERNS

3.2.1 Out-Gassing

The common aviation fuels are normally a single liquid phase. There may be conditions, however, where these fuels can become two phase (liquid and vapor) systems.

The gases comprising air are soluble in aviation fuels such that their concentration in the fuel is in equilibrium with the gases in the headspace of the storage tank or in a surge tank in the fuel supply system (*Figures 2-29 through 2-31*). When the pressure on the fuel is reduced or the fuel temperature is decreased, the gases become less soluble. Dissolved gases can evolve into a vapor phase and form gas bubbles. This phenomenon can result in fuel pump cavitation, fuel spills from tank vents, or virulent combustion instabilities during engine operation. Aircraft and engine fuel systems should be designed to handle evolving gases based on data previously presented in *Section 2.10*.

A discussion on vapor lock will be found under *Aviation Gasoline Issues* in *Section 3.3.1*.

3.2.2 Fuel System Icing Inhibitors

As discussed in *Section 1.1.3*, anti-icing or fuel system icing inhibitor (FSII) additives are available for both turbine fuels and aviation gasoline. FSII works by partitioning off free water to form a solution with a lower freezing temperature than water (like antifreeze in automobile use). FSII is required in most military fuels because most military aircraft do not have fuel heaters. FSII is also required for some turbine-powered, general aviation aircraft that do not have fuel heaters.

FSII Effects

Glycol ethers are not readily soluble in fuel and care must, therefore, be taken to achieve adequate mixing. Additive injection upstream of a centrifugal pump is an excellent way to ensure proper mixing. Complete solution of FSII in fuel requires the additive to have a very low dissolved water content and the fuel to have very little or no free water in it. Undissolved FSII can damage elastomers and other materials in the aircraft and fuel delivery system. Neat anti-icing additives are powerful solvents that can dissolve membrane filters used in particle detection and can peel interior coatings in receipt vessels. There is also preliminary evidence, still being investigated, that the neat anti-icing additive can attract and trap dissolved materials and components from other additives, even solid contaminants, forming a colloidal suspension that can plug filters. Such a colloidal suspension has been labelled *Apple Jelly*, see Reference 11 for more information.

FSII does not affect piston engine carburetor icing which is caused by the condensation and freezing of atmospheric moisture on throttle plates.

3.2.3 Fuel Lubricity

Aviation turbine fuel serves as a lubricant in fuel pumps, engine controls, and servo valves. Straight-run fuels normally contain boundary lubricants in trace amounts. These are primarily polar compounds containing oxygen, nitrogen, or sulfur. Such polar compounds form thin films on metal surfaces, protect against corrosion, and provide boundary lubrication. Lack of lubrication results in high friction and metal-to-metal contact leading to increased wear rates and possible scuffing. Severe refining conditions, such as hydrocracking, remove these natural lubricants from the fuel and severely hydrotreated or hydrocracked fuels are, therefore, more likely to have poor lubricity.

Measurement of Lubricity

Originally released as SAE-AIR 1794, and later as ASTM D 5001, the Ball On Cylinder Lubricity Evaluator (BOCLE) provides a measure of fuel lubricity under closely controlled conditions. In the test, a fixed 1/2 inch steel ball is pressed on a rotating cylinder lubricated by a thin fuel film under constant conditions of load, sliding speed, and atmospheric temperature and humidity. Lubricity is rated in terms of the wear scar on the test ball. The larger the scar, the lower the fuel lubricating properties. ARP 1797, a low lubricity endurance test, is used to evaluate the performance of fuel-lubricated aircraft pumps. ARP 1797 specifies the use of a poor lubricity fluid which causes a wear scar diameter (WSD) of 0.85 to 0.96 mm as determined by ASTM Test Method D 5001.

While there are a number of other lubricity measuring methods currently available and under constant comparison to BOCLE, experience continues to support the use of D 5001 results for turbine fuel use.

Effects of Low Lubricity Turbine Fuels

Low lubricity (*hard*) fuels exist worldwide. At the present time, it is not a significant issue in most locations due to co-mingling of fuels in pipelines and airport fuel systems. Research has shown as little as 10 percent of good lubricity fuel is required to enhance the inadequate lubricity properties of a poor fuel. There are, however, circumstances where an aircraft may be traveling a route in which low lubricity fuels are the only fuels available. In these cases, fuel pump life is observed to be shortened and, in at least one case, inflight pump failures have occurred. Operators' options include using corrosion inhibitor/lubricity agents, installing pump elements made of harder materials, or accepting higher wear rates. Since about 1990, OEMs have been producing pumps containing harder materials and supplying replacement pump elements of harder materials for equipment produced earlier.

Control of Lubricity

At this writing, lubricity is not controlled by ASTM D 1655 or D 6615. DEF STAN 91-91 includes provisions designed to ensure that compliant fuel will always have greater lubricity than ARP 1797 test fluid. Blending of a good and a poor fuel can result in a satisfactory fuel. The lubrication properties of fuels can also be improved by adding a corrosion inhibitor/lubricity improver meeting the MIL-PRF-25017 specification. Added to the fuel up to the approved maximum concentration level, the additives are not detrimental to thermal stability nor to the fuel's water separation characteristics.

Turbine fuel lubricity could be a bigger issue in the future as the refining industry responds to regulatory mandates requiring steep reduction in the sulfur content of gasoline and diesel. The concern is that the fraction of jet fuel batches having poor lubricity may become sufficiently large that inadequate protection is afforded by co-mingling alone.

3.2.4 Thermal Stability and Oxidative Stability

Aviation turbine fuels can undergo free radical reactions with dissolved molecular oxygen, leading to the formation of hydroperoxides, sediments, and surface deposits. In fuel storage at ambient temperatures, these oxidative reactions are usually not rapid, requiring months to occur to any significant extent. Storage stability problems are usually not encountered in commercial fuels which generally have minimal storage time.

Thermal oxidation reactions occur as a result of the exposure of fuel containing dissolved oxygen to high temperatures during delivery to engine components in aircraft. Thermal oxidation reactions can result in the formation of varnish-like surface deposits which can degrade heat transfer, interfere with the movement of close tolerance sliding and rotating parts found in fuel controls, and can lead to injector, spray bar and fuel nozzle plugging creating non-uniform fuel distribution.

Preventing Stability Problems

Proper manufacture and handling of fuels to minimize the presence of reactive olefins, heterocyclic compounds, and dissolved metals, also contributes to the reduction of stability problems. Storage and thermal oxidative stability differ, however, because a fuel's resistance to thermal oxidation generally improves with increased purification but storage stability often degrades when processed (e.g., treating with hydrogen removes trace natural antioxidants).

Both storage and thermal oxidation reactions proceed more readily in the presence of reactive components such as olefins and heterocyclic compounds in fuel, and can be catalyzed by dissolved metals. Copper, in particular, is a strong catalyst for oxidation reactions, thus is not used in commercial fuel storage systems. If contact with catalytic metals is unavoidable, then metal deactivator additive is used to chelate the dissolved metal in the fuel, rendering the metal non-catalytic. While antioxidants are effective at improving the storage stability of fuels, they do not generally improve thermal stability; JP-8+100 was developed by the military to increase fuel tolerance to elevated temperatures and resist thermal oxidative stresses in the engine fuel system. Dissolved oxygen removal prior to aircraft fueling has not proven practical.

3.2.5 Static Charging

The flow of fuel through filter monitors and filter separators, and to a lesser extent, strainers, screens and hoses, generates static electric charges within the fuel. Highly charged fuel can discharge in vapor spaces, generating a spark. Under certain conditions, this discharge can ignite fuel vapors.

Static dissipaters can be added to the fuel making it more conductive and to increase the rate of charge dissipation (relaxation) as discussed in *Section 1.1.3*. The use of such additives is required by Def Stan 91-91 and a number of military jet fuel specifications. The additive is not in general use in the U.S. and is permitted, but not required, by D 1655 or D 6615, because clay treatment is widely used in the U.S. and removes the additive. Other procedures are used to minimize static hazards.

Electrical bonding of conductive elements in systems during fuel flow does not prevent static buildup in the fuel but is required to minimize potential electrical differences that can lead to electrical discharges.

For further discussions on static electricity and static discharge, refer to ASTM Standard Guide D 4865, Coordinating Research Council documents CRC Report No. 583 and CRC Report No. 590, and API Recommended Practice 2003, Sixth Edition.

3.2.6 Aviation Turbine Fuel Filtration

Modern aviation fuel filter systems (filter/sePARATOR or filter monitor) are designed to remove free water and dirt from the turbine fuel. The API and the British Institute of Petroleum (IP) jointly publish specifications for the fuel filters used at terminals and in airports. Filter separators or filter monitors may be used at all points in the distribution system, but are required at terminals, airports, and into-airplane refuellers and hydrant servers. Correctly functioning aviation filtration removes free water from turbine fuel to concentrations below 15 ppm and solids to less than 1 mg/L.

Filter System Description and Problems

Filter/separators are two stage systems. The first stage is the filter/coalescer stage that functions by filtering dirt and causes water droplets to coalesce until they are large enough to drop to the vessel bottom where the water can be drained. The second stage is the separator stage where fuel flows through material that rejects any small water droplets still entrained in the fuel. Filter/separator systems may be disarmed (rendered ineffective) by fuel surfactants that adsorb on surfaces of coalescers, modifying surface activity and allowing water to pass through as small drops. These surfactants may also organize at the fuel/water interface, modifying the interfacial tension and stabilizing the formation of small water droplets. Filter separator performance is covered by API/IP specification 1581 and 1582.

Filter monitors are single stage systems that filter the fuel, passing it through material that absorbs free water. When saturated, monitors completely stop fuel flow. Filter monitors are generally unaffected by fuel-borne surfactants; however, the presence of incompletely dissolved FSII may cause water monitors to fail, permitting water transmission if high concentrations of DiEGME are present in the free water. It was originally thought this transmission would increase the differential pressure across the unit, but testing has proved there can be significant water transmission before the pressure drop begins to rise. Filter monitor performance is defined in API/IP specification 1583.

The additive package used to create JP-8+100 fuel includes powerful surfactants that disarm the conventional API 1581 3rd Edition coalescers very rapidly. More recent editions of API/IP 1581 include provision for category M100 filter/separators that have been successfully performance tested with JP-8+100 fuel.

3.2.7 Material Compatibility

Material compatibility with aviation turbine fuels is key to selecting metals and elastomers for aircraft fuel system construction, including piping, seals, filters, pumps, sealants, and fuel nozzles. Anytime a new alloy or material is selected for use, fuel compatibility must be assessed. Listed below are partial lists of common materials found suitable for, or banned from, use in fuel systems.

Metals

Table 3-1 categorizes metals that are satisfactory for use with hydrocarbon aircraft and missile fuels, and those which are not recommended.

Table 3-1. Satisfactory and Unsatisfactory Metals for Aircraft and Missile Fuels Applications

<i>Satisfactory</i>	<i>Unsatisfactory</i>
Aluminum and all its alloys	Bronze
Carbon Molybdenum Steel	Nickel
1/2 to 3% Nickel Steel	Copper
4 to 6% Chromium Molybdenum Steel	Zinc
300 Series Stainless Steel	Cadmium
400 Series Stainless Steel	Brass
Monel	Iron

Elastomers and Rubber

The materials in **Table 3-2** are recommended for use with aircraft and missile kerosine fuels.¹ Selection of materials is dependant on the application's temperature range, loading, vibration, and other mechanical and physical requirements. Consultation with a polymer expert during the design of a fuel system is important in order to determine physical and mechanical limitations of a specific polymeric material.

Table 3-2. Elastomers and Rubber Recommended for Use in Turbine Fuels

Nylon (Polyamide)	Fluorothene A
Kel-F	Vinylite
Trithene	Teflon™ (Tetrafluoroethylene)
High Density Polyethylene	Fluorel
Buna N (less than 250°F)	Viton (Fluorocarbon)
Hydrogenated Nitrile Butyl (HNBR)	Fluorosilicone
Kalrez	Polyacrylate
Chemraz (FFKM)	Epichlorohydrin

¹ Compatibility data taken from the *Chemical Resistance Guide for Elastomers*. All results are believed to be based on valid laboratory or field tests; however, no guarantee is expressed or implied as to results which will be obtained by the user. It is recommended that the user test the anticipated combinations in their own laboratory before committing their product to any application.

The materials listed in **Table 3-3** are not recommended for use with aviation turbine fuels.

Table 3-3. Elastomers and Rubber Not Recommended for Use in Turbine Fuels

Low Density Polyethylene (LDPE)	Ethylene Propylene Dimer (EPDM)
Chloroprene	Styrene Butadiene (SBR)
Isobutylene Isoprene (Butyl)	Polybutadiene
Natural Rubber	Silicone

3.3 AVIATION GASOLINE ISSUES

3.3.1 Vapor Lock

Vapor lock occurs when volatile components of gasoline or turbine fuels evaporate in a closed system, increasing the total volume beyond the capacity of the fuel pump, thereby starving the system of liquid fuel. The evaporation of these light components is a function of fuel pressure and temperature. Fuel specifications control fuel vapor pressure and distillation limits to allow adequate volatility for starting while avoiding excessive volatility that leads to vapor lock. These specifications also establish design targets for aircraft fuel systems. To avoid the effects of vapor lock, important engineering considerations include eliminating fuel line hot spots and locating fuel pressure drop points where vapor formation is not consequential.

3.3.2 Misfueling

Misfueling aircraft is a serious problem; aviation gasoline and aviation turbine fuels are very different products intended for use in fundamentally different engine designs. While it is possible to operate a gas turbine engine on aviation gasoline, it may be detrimental to the engine over long term exposure. For many military turbine engine applications, aviation and motor gasoline have long been *emergency* fuels with limited operational use permitting the aircraft to leave a combat area, and requiring significant after-action engine maintenance. In a situation such as this, the two issues of concern are presence of lead in the fuel that can plate engine hot section materials and the high volatility of the gasoline that can limit both aircraft operating altitudes and engine operation.

A spark ignition piston engine powered aircraft will not operate on aviation turbine fuels. Misfueling a spark ignition reciprocating engine powered aircraft with turbine fuel results in fairly rapid engine failure, frequently right after takeoff. Misfueling can occur because such aircraft are normally fueled overwing (similar to automotive fueling), and certain general aviation turbine-powered aircraft are fueled the same way.

Several steps have been taken to eliminate misfueling. One step is the application of color-coded decals to the aircraft filler caps and matching decals on fuel nozzles and hoses. Another step is the standardization of nozzle and filler opening shapes and sizes to physically prevent misfueling of aircraft. Note that some older aircraft cannot comply with these standards, leading to the use of nozzle adapters that can compromise the effectiveness of the system. FAA Advisory Circular 20-122 addresses the misfueling issue.

3.3.3 Use of Unleaded Automotive Gasoline/82UL Gasoline

Some operators of piston aircraft have successfully used unleaded automotive gasoline (autogas) for many years. The use of autogas in aircraft requires the owner/operator to obtain a supplemental type certificate (STC) from the appropriate aviation regulatory agency. This procedure helps to ensure that the significant issues involved in the successful aviation use of autogas are appropriately addressed.

Autogas is more prone to vapor lock because it is more volatile than aviation gasoline. In some aircraft, the routing of lines, placement of pumps, and even the number of bends in a fuel line can provide conditions that increase the tendency to vapor lock. Such aircraft may not give acceptable performance with autogas.

Autogas has lower octane ratings than the Avgas 100 grade, thus the octane requirements of many high compression piston engines are not satisfied by autogas. Other properties of autogas also vary much more than

those of aviation gasoline. In autogas, the distillation range and volatility is adjusted for seasonal and regional temperature variations; in aviation gasoline they are not. There is less control of fuel additives for autogas than aviation gasoline, and the requirements for autogas handling and cleanliness are not as strict as those for aviation gasoline.

Grade 82 UL Avgas, ASTM Specification D 6227-00, can be blended from autogas streams in the refinery. The specification provides the necessary restrictions on properties for aircraft use, and combines these with the high availability of the autogas streams.

3.3.4 Other Lead Effects

Over the years, piston engines have been designed to accommodate the formation of lead combustion products. Although a potential problem in other locations, lead deposits have acted as a solid lubricant between the exhaust valve faces and the valve seats, and operating on unleaded aviation gasoline has caused excessive wear in this location. To overcome this design limitation, the major piston engine manufacturers have recommended a break-in period using leaded fuels, even when the aircraft would be operating on an unleaded fuel. With the elimination of leaded fuels, the problem is overcome by the installation of hardened valve seats.

3.3.5 Materials Compatibility

Elastomers and Rubbers

The materials in **Table 3-4** are recommended for use with aviation gasoline fuels.¹ Material selection is dependent on the temperature range of the application, loading, vibration, and other mechanical and physical requirements. Consultation with a polymer expert during the design of a fuel system is important in order to determine physical and mechanical limitations of a specific polymeric material.

Table 3-4. Materials Recommended for Use with Aviation Gasoline Fuels

Kalrez® (less than 113°F)
Teflon (Tetrafluoroethylene)
Flurosilicone (less than 70°F)
Buna N (less than 200°F)
Nylon 11 (less than 140°F)

The materials listed in **Table 3-5** are not recommended for use in aviation gasoline fuels.

Table 3-5. Materials Not Recommended for Use with Aviation Gasoline Fuels

Low Density Polyethylene (LDPE)
Chloroprene
Styrene Butadiene (SBR)
Ethylene Propylene Dimer (EPDM)
Isobutylene Isoprene (Butyl)
Polybutadiene Natural Rubber
Silicone

¹ Compatibility data taken from *Chemical Resistance Guide for Elastomers*. All results are believed to be based on valid laboratory or field tests; however, no guarantee is expressed or implied as to results which will be obtained by the user. It is recommended that the user test the anticipated combinations in his own laboratory before committing his product to any application.

3.4 TOXICITY

The toxicity rating levels of turbine fuels, aviation and automotive gasolines, and other fuels mentioned in this document can be found in the Material Safety and Data Sheets (MSDS) that accompany shipments.

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4. SPECTRAL CHARACTERIZATION

4.1 INTRODUCTION

A comprehensive molecular spectroscopic investigation of five military-grade aviation fuels has been performed by the Air Force Research Laboratories at WPAFB, Ohio, for the purpose of cataloging their basic spectral parameters. Included were four fuels that were formulated for gas turbine engines (JP-8 or Jet A/A-1, JP-5, JP-7, and JP-TS) representing complex mixtures of aliphatic, olefinic, and aromatic compounds, and one single-component missile fuel (JP-10). Data obtained using molecular-spectroscopic methods that are sensitive to chemical functionality (Fourier-transform infrared absorption, near-infrared absorption, and Raman scattering) reveal significant similarities between the gas turbine engine fuels that can be attributed to the high degree of similarity in the composition of the fuels. Only the single-component missile fuel (JP-10) exhibits unique spectroscopic signatures. Data obtained using ultraviolet-visible-absorption and fluorescence-emission spectroscopies reveal clear differences in each of the fuels. Because of the nature of absorption and fluorescence processes (probing electronic transitions within individual molecules), these methods favor the aromatic and olefinic constituents of fuel, and are extremely sensitive to subtle changes in composition. The data obtained with these spectroscopic techniques are presented and discussed in the context of fuel composition. Gas-chromatographic analyses are provided as examples of the molecular spectra of the fuels, and chromatograms obtained for motor gasoline and diesel fuel are included. The chromatograms serve to demonstrate the complex nature of the fuels.

While these data do not represent reference spectra typical of all aviation fuels, they do provide some indication of the general spectroscopic features characteristic of such fuels. This information may be utilized to guide the development and execution of experimental and computational fuel studies that involve fuel spectroscopy. Those interested in additional spectroscopic information regarding aviation fuels and related compounds are referred to the representative literature identified in *References* at the end of this section.

4.2 EXPERIMENTAL

4.2.1 Materials

The jet propulsion fuels studied (JP-4, JP-5, JP-7, JP-8, JP-10, JP-TS, Jet A/A-1), motor gasoline (mogas/autogas), and diesel fuel (DF-2) were all obtained in-house. Hexane (spectroscopy grade) was obtained from Fisher Scientific and used as received.

With the exception of JP-10, the fuels used in this study are complex mixtures of aliphatic, olefinic, and aromatic compounds. JP-10, which was included for contrast, is a synthetic, single-component missile fuel (exo-tetrahydro-di [cyclopentadiene]). JP-8, Jet A/A-1, JP-5, JP-7, and JP-TS are gas turbine fuels designed to operate in air-breathing engines. Jet A/A-1 is the commercial equivalent of JP-8, the primary fuel for the U.S. Air Force. The principal difference between the two is a suite of additives included in JP-8 as required by military specifications. All of the JP fuels contain additives that are specific to their operational parameters and contribute to the complexity of the fuels. They are considered part of the fuel for the purposes of this study. JP-5, the primary fuel for the U.S. Navy, is formulated to have a higher flash point, making it safer for use on naval vessels. JP-7 and JP-TS are specialty fuels designed for the SR-71 Blackbird and U-2 aircraft, respectively. These fuels possess thermal-stability (JP-7 and JP-TS) and cold-flow characteristics (JP-TS) that are superior to those of JP-8 and Jet A/A-1.

4.2.2 Measurements

4.2.2.1 Ultraviolet-Visible Absorption

Ultraviolet-visible absorption spectra were recorded on a computer-controlled Shimadzu UVPC-2101 spectrophotometer. The fuels were studied in a 1 cm quartz cuvette. To obtain complete absorption spectra, serial dilutions were performed using spectroscopy-grade hexane. All regions of the absorption spectra were collected within the linear response range of the spectrometer (0 to 1.0 optical density). To obtain the final spectrum, each region was

corrected by the appropriate dilution factor and joined using commercially available spectral-graphing software. Background spectra were recorded separately and subtracted from the fuel spectra.

4.2.2.2 Fluorescence Emission

Fluorescence spectra were obtained on a Spex Fluorolog-2 photon-counting emission spectrometer equipped with a 450-Watt (W) xenon source and a Hamamatsu R928 photomultiplier tube operated at -950 V. Samples were studied under optically dilute conditions (optical densities ~0.1 at the excitation wavelength) in a 1 cm quartz cuvette with source, sample, and detector configured in right-angle geometry. All fluorescence spectra were corrected for the nonlinear instrumental response of the spectrometer using predetermined correction factors.

4.2.2.3 Near-Infrared Absorption

Near-infrared absorption spectra were obtained on a Shimadzu 3100-UVPC equipped with a PbS detector. The fuels were studied neat using a short-path (2 mm) quartz cuvette. No solvent background was subtracted from the observed spectra. An empty quartz cuvette was checked for contributions to the absorption spectra, and none were found within the region studied.

4.2.2.4 Infrared Absorption

Infrared-absorption measurements were made on a Nicolet Magna-IR 550 FT-IR spectrometer. A pair of KBr salt plates was used to record the spectra of the neat fuels. Before the fuel spectra were obtained, the instrument was purged with a slow stream of nitrogen gas until all signals from ambient water and CO were removed. The fuel spectra were accumulated over 200 scans at a resolution of 2 cm^{-1} .

4.2.2.5 Raman Scattering

Raman-scattering spectra were recorded using a home-built spectrometer. The source was a Schwartz Electro-Optics Titan continuous-wave Ti:sapphire laser operated at 794.7 nanometer (nm) with an output power of ~700 milliwatts (mW). This laser was pumped by a Spectra Physics Millennia Nd:YVO₄ laser producing 5.0 W at 532 nm. A narrow band-pass filter (3 nm FWHM) centered at 794.7 nm was used to eliminate extraneous emissions from the Ti:sapphire system yielding transmittance through the filter of ~30 percent. The Raman signal was monitored without polarization optics through an Instruments SA HR460 spectrograph equipped with a liquid nitrogen cooled CCD detector. Entrance and exit slits on the HR460 spectrograph were set at 0.1 mm. A Kaiser holographic notch filter was employed to reject Rayleigh-scattered laser light. Neat samples of the fuels were studied in a 1 cm quartz cuvette with source, sample, and detector configured in right-angle geometry. The Raman spectra were not corrected for the nonlinear responses of the detection system.

4.2.2.6 Gas Chromatography – Mass Spectrometry

Gas chromatograms of the fuels were obtained using an HP-5890 gas chromatograph equipped with a Restek RTX-5 amine 30-m capillary column employing helium as the carrier gas and an HP-5971 mass spectrometer as the detector. The analysis parameters for the provided chromatograms included carrier gas at a constant pressure of 10 psi, an injector temperature of 280°C, and an oven temperature profile of 40° to 300°C at 5°C/min.

4.3 SPECTRAL RESULTS

The spectroscopy of the fuels is dominated by the fact that the fuels are complex mixtures. The observed spectra represent the average behavior of the contributing compounds. Changes in the relative concentrations of the compounds or in the compositional makeup of the fuel mixtures can produce different spectra for similar fuels. The spectra presented herein should not be taken as absolute (or used as standards), but rather as indications of what might be expected in terms of spectral transitions for a particular fuel mixture.

4.3.1 Ultraviolet-Visible Absorption

Ultraviolet-visible absorption spectra covering the wavelength range 190 to 850 nm (*Figures 4-1* through *4-5*) were collected for each fuel. No absorption features above a wavelength of 450 nm were observed for any of the fuels in this study (although reports of Jet A/A-1 samples with distinct green, pink, or yellow tints have been made). Thus, an optical-access window exists between ~450 and 850 nm where spectral access can be achieved.

Such a window has numerous potential uses; for example, chemically modified additives employing dyes possessing absorption features in the 450 to 850 nm range could be detected and quantified easily without interference from the natural absorption of the fuels. Similarly, optical sensors that measure characteristics of the fuel (e.g., viscosity, conductivity, water content, component concentrations, etc.) could function without fuel background interference within this spectral region.

The fuels possess an optical cutoff in the 300 to 350 nm region. Below this region, the fuels become opaque, absorbing most of the incident light. To examine the absorption characteristics below this region, the fuels were diluted with a simple aliphatic hydrocarbon solvent (hexane) that has no significant absorption contribution above 200 nm. Examination of the dilution profiles of the fuels JP-8, Jet A/A-1, JP-5, JP-7, and JP-TS reveals several common absorption features. For example, each of the fuels exhibits a sharp shoulder-like peak between 300 and 350 nm, a strong absorption peak between 250 and 300 nm, and a shoulder or peak between 200 and 250 nm. Absorption in these regions is due to the aromatics, olefins, and heteroatom-containing compounds that are present to varying degrees in each fuel. The similarities in the diluted absorption spectra result from the common compositional makeup of the fuels. While the concentrations of the aromatics, olefins, and heteroatom-containing compounds may vary from fuel to fuel, the types of compounds found in each fuel are very similar.

An interesting consequence of the similarities in the dilute absorption spectra is the potential for comparing the relative concentrations of the aromatics in the fuels. A straightforward way to examine the fuel spectra within a common frame of reference is to apply Beer's Law expressed as

$$a_{\lambda} = \epsilon_{\lambda} cb \quad \text{Equation 1}$$

where a_{λ} is the measured absorption at some wavelength λ , c is the concentration of the absorbing component, b is the optical path length, and ϵ_{λ} is the molar absorptivity at wavelength λ . Ideally, the observed absorption could be divided by the molar absorptivity and the optical path length to yield the concentration. But, because the fuels are complex mixtures, they cannot be described by a molar absorptivity. As an alternative, Equation No. 1 can be rearranged in terms of the absorptivity, and a substitution of fuel density for concentration (also difficult to assign) can be made. Thus,

$$\epsilon_{\lambda} = a_{\lambda}/\rho b \quad \text{Equation 2}$$

where ρ is the fuel density (g/mL) and ϵ_{λ} is now a density-based absorptivity with units of mL/gcm. Using densities obtained from the CRC Handbook of Aviation Fuel Properties, **Figures 4-1** through **4-5** have been plotted in terms of Equation No. 2. Based on the absorption feature located between 250 and 300 nm, the absorptivities follow the order Jet A/A-1 (JP-8) and JP-5 (~15,000 mL/gcm) > JP-TS (~300 mL/gcm) > JP-7 (~80 mL/gcm). The trends are in general agreement with the aromatic content of the fuels. The intensities observed for JP-10 (**Figure 4-5**) are unusual because JP-10 is a single-component aliphatic hydrocarbon with absorption features at lower wavelengths (higher energies). The observed absorption features in the 250-300 nm range arise due to additives, contamination from other fuels, or both. These features depend highly upon the fuel history.

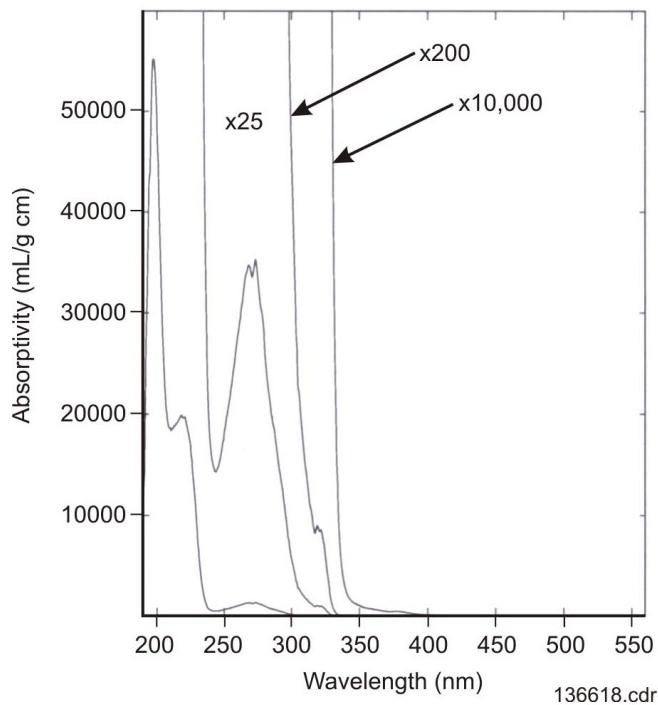


Figure 4-1. Ultraviolet-Visible Absorption Spectrum of Jet A/A-1 (Representative of JP-8 and JP-8+100); Multiplication Factors Indicate Values Used To Place All Absorption Spectrum Sections on Same Scale

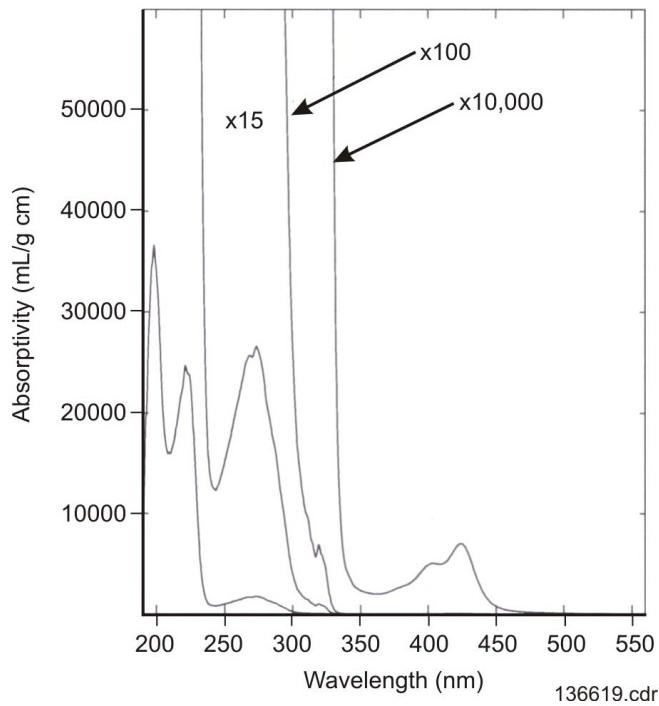


Figure 4-2. Ultraviolet-Visible Absorption Spectrum of JP-5; Multiplication Factors Indicate the Values Used To Place All Sections of the Absorption Spectrum on the Same Scale

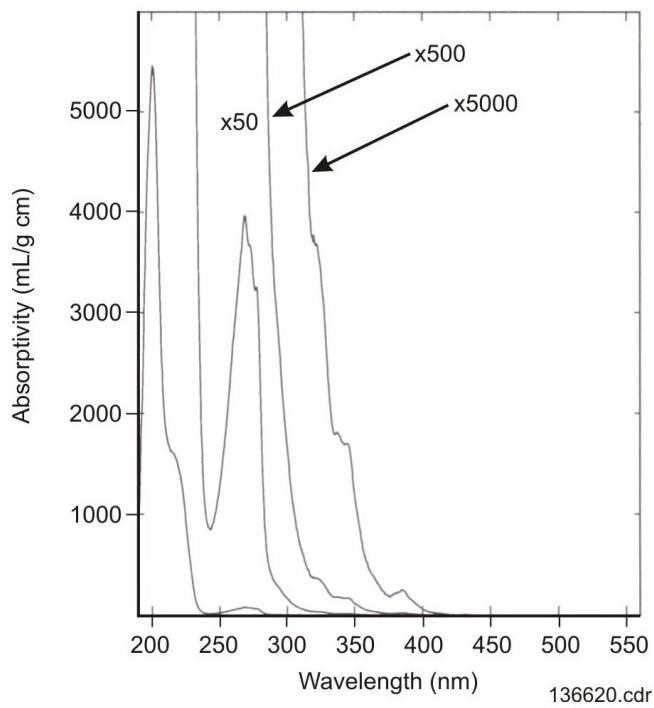


Figure 4-3. Ultraviolet-Visible Absorption Spectrum of JP-7; Multiplication Factors Indicate the Values Used To Place All Sections of the Absorption Spectrum on the Same Scale

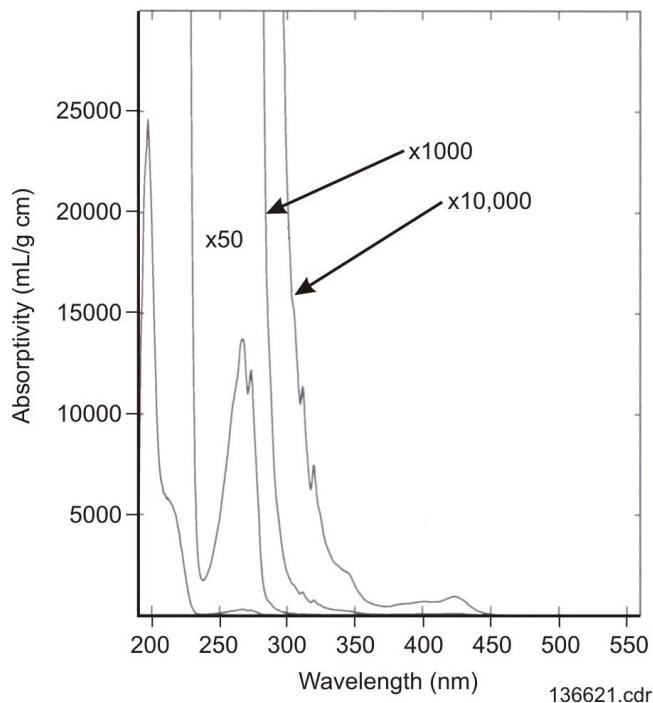


Figure 4-4. Ultraviolet-Visible Absorption Spectrum of JP-TS; Multiplication Factors Indicate the Values Used To Place All Sections of the Absorption Spectrum on the Same Scale

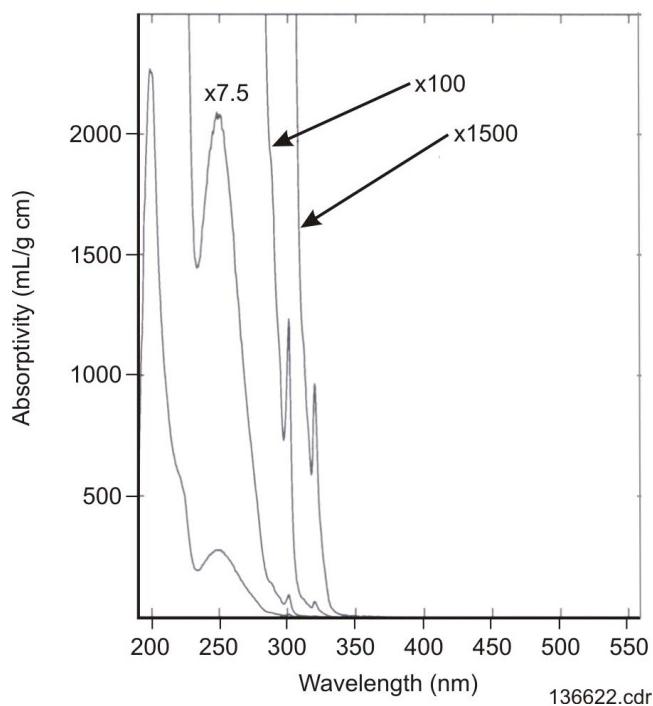


Figure 4-5. Ultraviolet-Visible Absorption Spectrum of JP-10; Multiplication Factors Indicate the Values Used To Place All Sections of the Absorption Spectrum on the Same Scale

4.3.2 Fluorescence Emission

Data obtained using fluorescence-emission methods are displayed in **Figures 4-6** through **4-10**. The first and most dramatic characteristic common to each of the fuels is the extreme excitation wavelength dependence of the fluorescence spectra. For example, the emission spectra data of Jet A/A-1 (**Figure 4-6**) were collected with excitation from 280 to 500 nm. As is evident, each spectrum is distinct. Interestingly, the spectra appear to have some similarity in three regions: 80 to 330 nm, 340 to 400 nm, and 425 to 500 nm. The same pattern is also observed for the fuels JP-7 and JP-TS (**Figures 4-7** and **4-8**). JP-5 and JP-10 also exhibit wavelength excitation dependence however, their spectra are much less complicated (**Figures 4-9** and **4-10**).

The observed excitation wavelength dependence of the fuel spectra is a result of the complex nature of the fuel mixtures. Many individual fluorophors are present in the fuels, each with its own absorption and fluorescence characteristics. The observed fluorescence spectrum at any given excitation wavelength is a result of the combined emissions from all of the compounds that absorb at that particular excitation wavelength and emit with sufficiently high quantum yield to be detected. The regions of spectral similarity are probably a result of similarities in the compositional makeup and the relative absorptivities of the contributing fluorophors in that excitation region. Because of the extreme dependence of the observed fluorescence spectra on excitation wavelength, quantitative use of the spectral profiles is rather challenging. For example, when exciting in regions of similarity, semi-quantitative applications may be possible for such activities as gaging the effects of an external variable (e.g., temperature or pressure) on the composition or behavior of the fuels.

Except for the spectral profile, the fluorescence quantum yield (Φ_F) is the most fundamental fluorescence-emission parameter representing the fraction of absorbed photons that are subsequently emitted. While this parameter is of great importance in understanding the photophysical behavior of a single compound or system, its value in studying aviation fuels may be rather limited. As a matter of record, the observed relative fluorescence quantum yields obtained under air-saturated conditions were determined as a function of excitation wavelength for each fuel. **Figure 4-11** shows the yield for each fuel plotted as a function of excitation wavelength. For comparison

purposes, the yields have been normalized at 300 nm ($\Phi_F/\Phi_{F@300\text{nm}}$). Each fuel exhibits a distinctive trend with excitation wavelength. Where the absorption spectra indicate similarities in the bulk aromatic compositions of the fuels, the fluorescence quantum yields indicate differences.

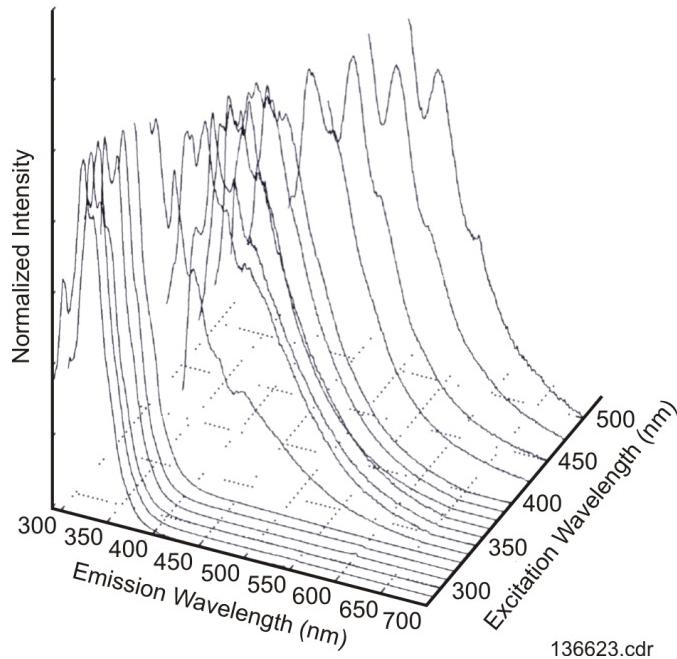


Figure 4-6. Fluorescence Spectra of Jet A/A-1 (Representative of JP-8 and JP-8+100)
Recorded as a Function of Excitation Wavelength

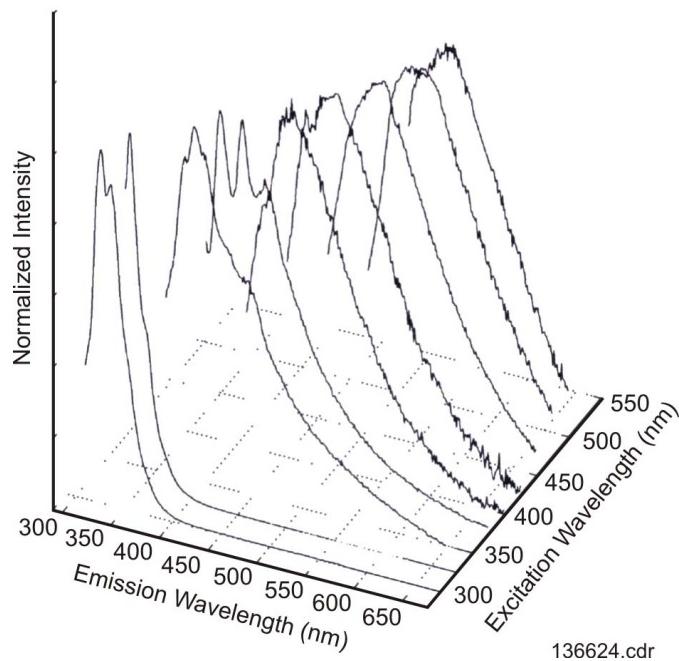


Figure 4-7. Fluorescence Spectra of JP-5 Recorded as a Function of Excitation Wavelength

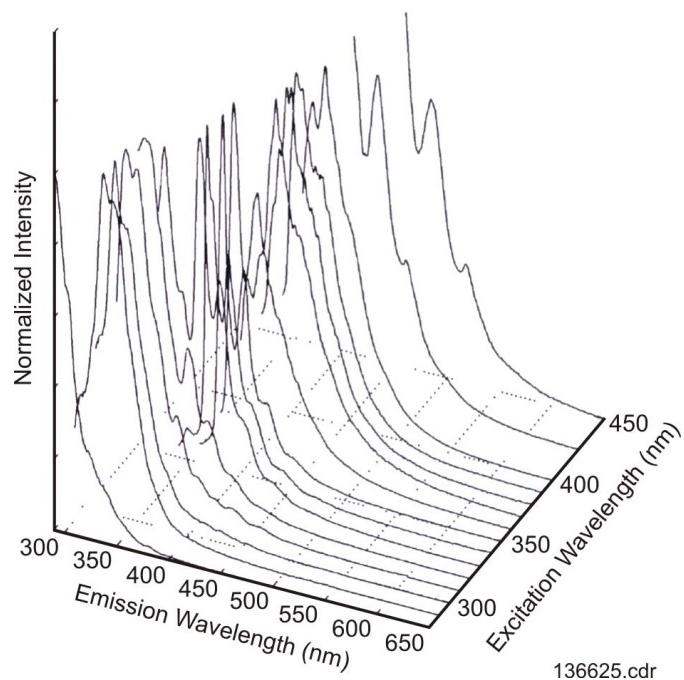


Figure 4-8. Fluorescence Spectra of JP-7 Recorded as a Function of Excitation Wavelength

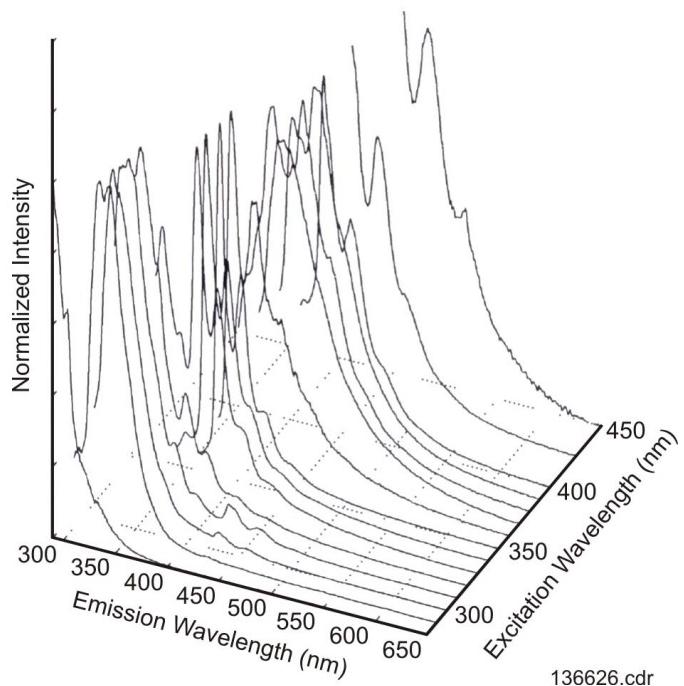


Figure 4-9. Fluorescence Spectra of JP-TS Recorded as a Function of Excitation Wavelength

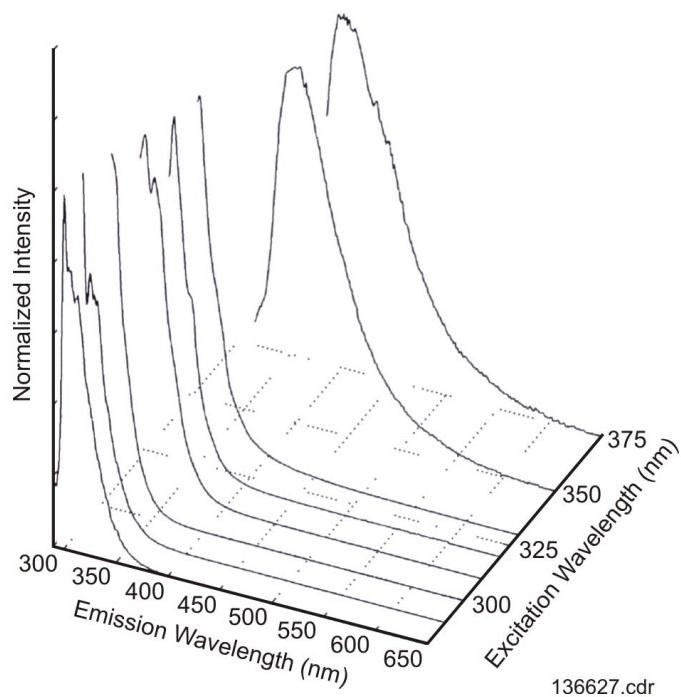


Figure 4-10. Fluorescence Spectra of JP-10 Recorded as a Function of Excitation Wavelength

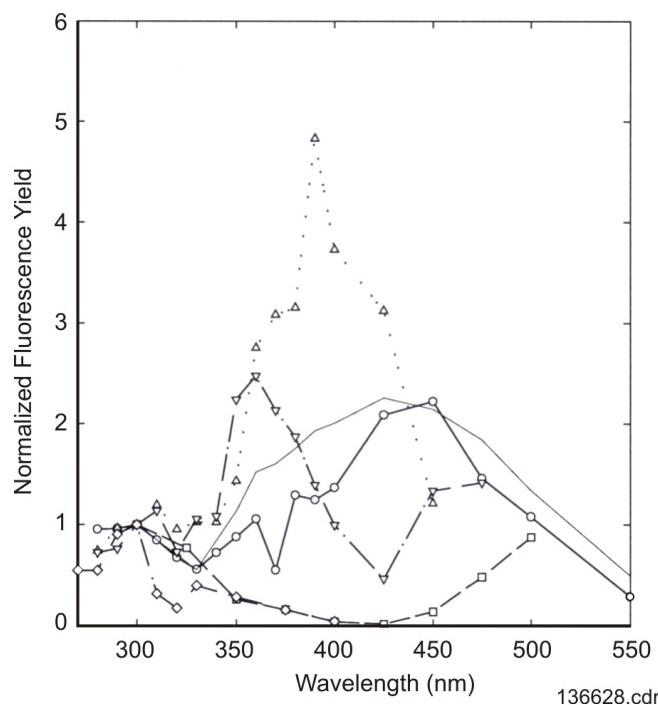


Figure 4-11. Normalized Fluorescence Quantum Yields of the Fuels as a Function of Excitation Wavelength: Jet A/A-1 (\circ), JP-5 (\square), JP-7 (\triangle), JP-TS (∇), and JP-10

4.3.3 Infrared Absorption

Infrared absorption (IR), Raman-scattering, and near-infrared (NIR) absorption methods differ from ultraviolet-visible absorption and fluorescence-emission techniques in that they provide chemical information. These spectroscopic methods yield absorption bands or scattering peaks that are characteristic of particular functional groups (e.g., C-H, C-C, C=C, S-H, and -OH). Consequently, detailed chemical information can be obtained while an external variable is changed (e.g., temperature or pressure). Unfortunately, these methods tend to be less sensitive than ultraviolet-visible absorption and fluorescence emission. As a result, the spectra obtained are more representative of the bulk-fuel components (aliphatic hydrocarbons) than of the aromatics and olefins.

Shown in a single figure, the infrared absorption spectra of gas turbine fuels JP-8, Jet A/A-1, JP-5, JP-7, and JP-TS have nearly identical spectra (*Figure 4-12a*). The strongest absorptions – a grouping of three sharp peaks located in the 2,900 cm^{-1} region – are due to aliphatic C-H stretches. There is no evidence of vinylic, aromatic, acetylenic, or cyclopropyl hydrogens since these absorptions would be observed beyond 3,000 cm^{-1} . Two somewhat weaker absorptions occur at $\sim 1,460$ and $1,370 \text{ cm}^{-1}$ and are attributed to methylene (CH_2) and methyl (CH_3) groups, respectively. A very weak absorption near $1,600 \text{ cm}^{-1}$ is probably due to the C=C stretch. No significant absorptions were observed in the fingerprint region (1,500 to 500 cm^{-1}) for any of the fuels. The infrared-absorption spectrum for JP-10 is different (*Figure 4-12b*). Again, the strongest absorptions are due to the aliphatic C-H stretches however, the grouping contains two sharp peaks rather than three. Another significant absorption feature is observed around $1,460 \text{ cm}^{-1}$ and is attributed to the methylene (CH_2) functional group. Unlike the other fuels, this band is resolved into four peaks located at 1,477, 1,468, 1,456, and $1,448 \text{ cm}^{-1}$. JP-10 also exhibits detail in the fingerprint region of the spectrum (*References 6 and 3*).

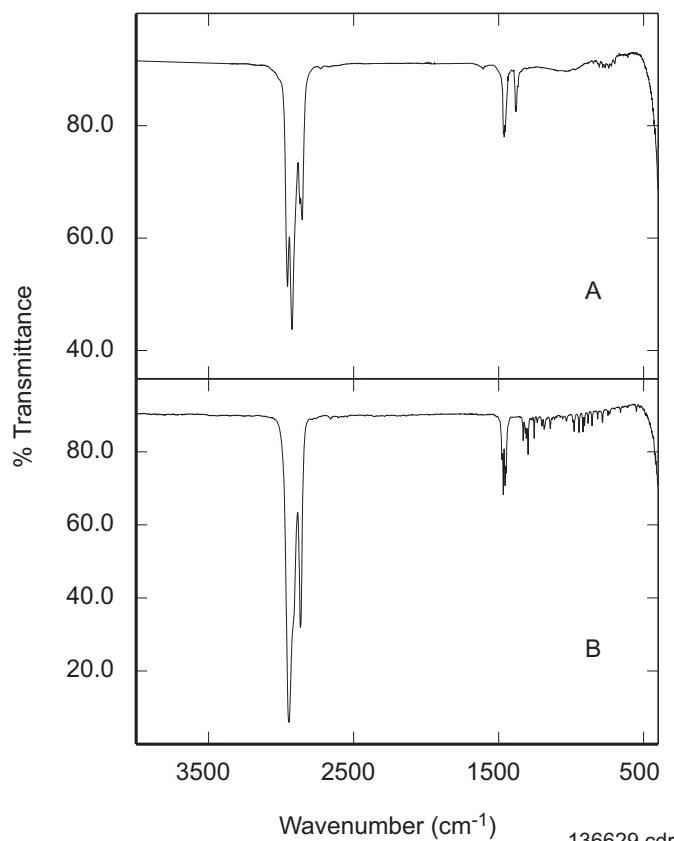


Figure 4-12. Infrared-Absorption Spectra of (A) Jet A/A-1 (Representative of JP-8, JP-8+100, JP-5, JP-7, and JP-TS) and (B) JP-10

4.3.4 Raman Scattering

Raman spectra were collected in the wave number range 2,000-200 cm^{-1} . For JP-8, Jet A/A-1, JP-5, JP-7, and JP-TS fuels, the spectra are fairly simple (*Figure 4-13a*). The strongest peak is located at $\sim 1,450 \text{ cm}^{-1}$ and is due to CH_2 and CH_3 deformations in n-alkanes. A weak set of peaks associated with various C=C stretches is located at $\sim 1,600 \text{ cm}^{-1}$. The remaining spectral region (1,400-200 cm^{-1}) contains peaks associated with the vibrations of paraffins, cycloparaffins, olefins, and aromatics that constitute the fuel mixtures. Very subtle differences in the relative peak intensities and backgrounds of the fuels in this region can be observed. The Raman spectrum of JP-10 is much more complex (*Figure 4-13b*). Because the fuel is a single component with substantial structural symmetry, the 1,400-200 cm^{-1} region is rich and very well defined. This region provides an excellent fingerprint for the identification of JP-10. In addition to the fingerprint region, a strong peak at approximately 1,450 cm^{-1} is also observed. (References 6 and 3).

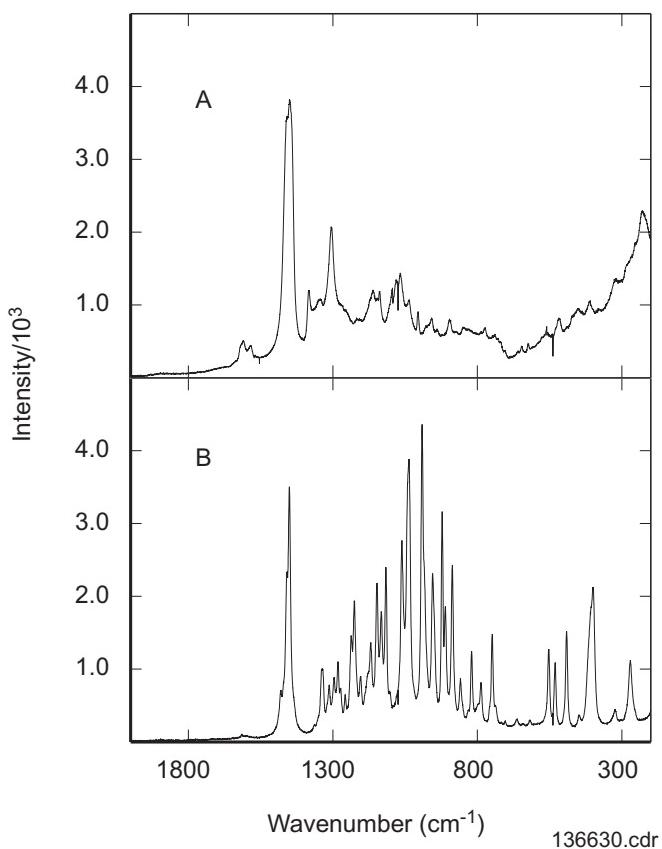


Figure 4-13. Raman-Scattering Spectra of (A) Jet A/A-1 (Representative of JP-8, JP-8+100, JP-5, JP-7, and JP-TS), and (B) JP-10

4.3.5 Near-Infrared Absorption

The near-infrared absorption spectra of JP-8, Jet A/A-1, JP-5, JP-7, and JP-TS are represented by the single spectrum in *Figure 4-14a*. The spectrum contains several absorption features that are characteristic of hydrocarbon solvents (*References 6 and 3*). Although not shown, strong absorption (nearly 0 percent transmittance through a 2-mm path length) is observed in the 2,300 to 2,500 nm region. JP-10 exhibits absorption in the same regions as the other fuels, but its structural features are noticeably different (*Figure 4-14b*). As in the case of the ultraviolet-visible absorption data, the near-infrared absorption data are plotted in terms of density-based absorptivity units (mL/g cm). The absorptivity values are three to four orders of magnitude lower than those obtained for the ultraviolet-visible spectra. Unlike the ultraviolet-visible results, the near-infrared absorptivity values are fairly constant for all the fuels.

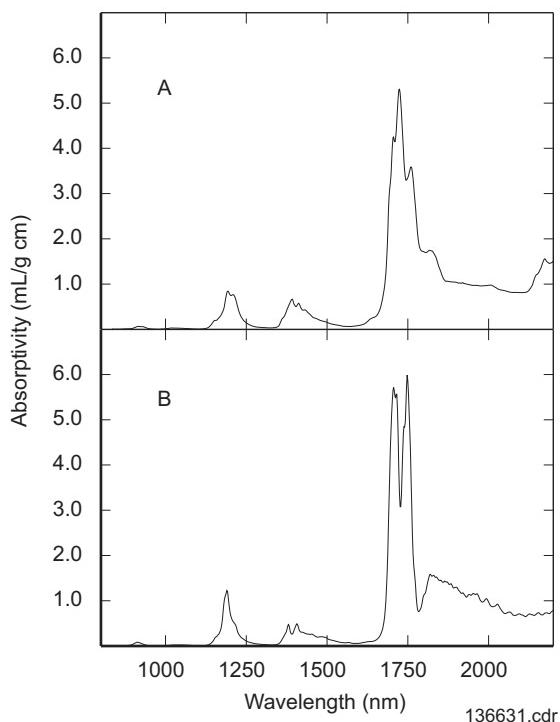


Figure 4-14. Near-Infrared Absorption Spectra of (A) Jet A/A-1 (Representative of JP-8, JP-8+100, JP-5, JP-7, and JP-TS) and (B) JP-10

4.4 GAS CHROMATOGRAPHY

Gas chromatography is a primary method for analyzing hydrocarbon fuels. The technique is based on the separation of complex mixtures of volatile substances between a stationary and a mobile phase (*Reference 7*). The distribution, or partitioning, of the volatile substances between the two phases determines the extent of separation and the chromatographic pattern (chromatogram) for a given fuel. Unlike the molecular-spectroscopic methods discussed above, gas chromatography does not provide a unique result. Instead, the chromatogram obtained for a given fuel is a function of the instrument parameters (i.e., column type, carrier gas and flow rate, and oven temperature profile). Thus, quantitative comparisons of different fuels or different lots of a single fuel must be performed using similar instruments and parameters. The chromatograms presented here are examples for the indicated fuels and serve only to demonstrate the complex nature of these fuel mixtures.

4.4.1 Aviation Fuels

Chromatograms of JP-8, Jet A/A-1, JP-5, JP-7, JP-TS, and JP-4 aviation fuels are shown in *Figures 4-15* and *4-16*. For the fuels JP-8 and Jet A/A-1, no significant differences in the chromatograms were observed (*Figure 4-15*), except for very subtle differences in the relative intensities of some of the peaks. These results mirror those obtained using the molecular-spectroscopic methods. JP-8 and Jet A/A-1 cannot be differentiated under routine analysis conditions. Similarly, it is difficult to distinguish JP-8 from JP-5, since both fuels display very similar chromatographic profiles (*Figure 4-16*). However, a distinguishable difference exists in the relative contributions of the various components, which can be most easily observed for the peaks labeled C12, C14, and C16. Contrary to the above results, JP-7, JP-TS, and JP-4 are easily differentiated from JP-8 (Jet A/A-1) and JP-5, and from each other (*Figure 4-16*). The differences in the chromatographic patterns arise due to differences in the compositions of the fuels. Compared to the molecular-spectroscopic methods and based on the results obtained, gas chromatography is a superior method for fuel identification.

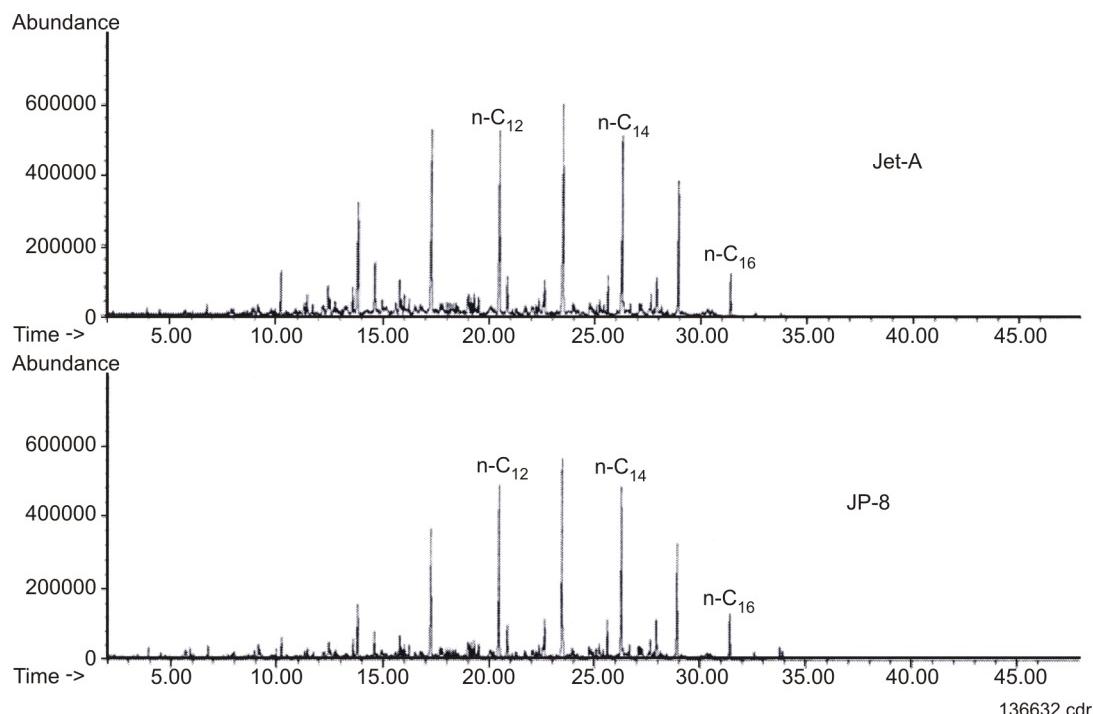


Figure 4-15. Gas Chromatograms of Jet A/A-1 and JP-8

4.4.2 Ground Fuels

Mogas (conforms to MIL-SPEC VU-G-1690, autogas) and diesel fuel (DF-2) gas chromatograms are shown for comparison purposes (*Figure 4-17*). Again, differentiation of the various fuels can be easily accomplished because of the significant differences in the chromatographic profiles. Mogas contains a substantial high-volatility fraction as evidenced by the large number of significant early-eluting peaks (retention times less than 15 min.). Of the aviation fuels, only JP-4 displays significant peaks over the same retention-time range. JP-4 also contains substantial concentrations of lower volatility compounds that are not present in Mogas as demonstrated by the peaks labeled C12, C14, and C16. Unlike any of the other fuels, DF-2 possesses significant contributions from peaks greater than C16 (*Figure 4-17*).

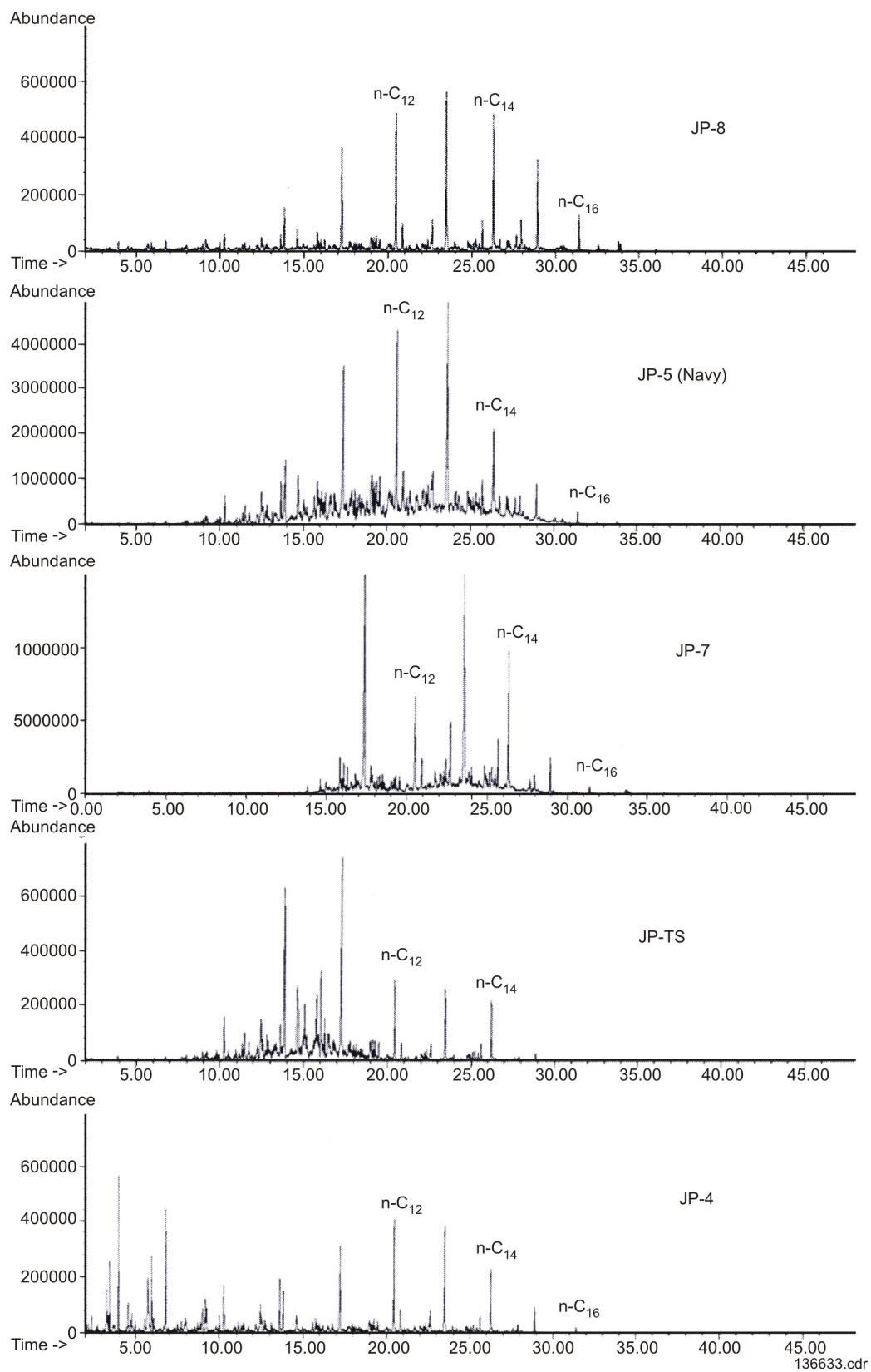


Figure 4-16. Gas Chromatograms of a Series of Military-Specification Aviation Fuels

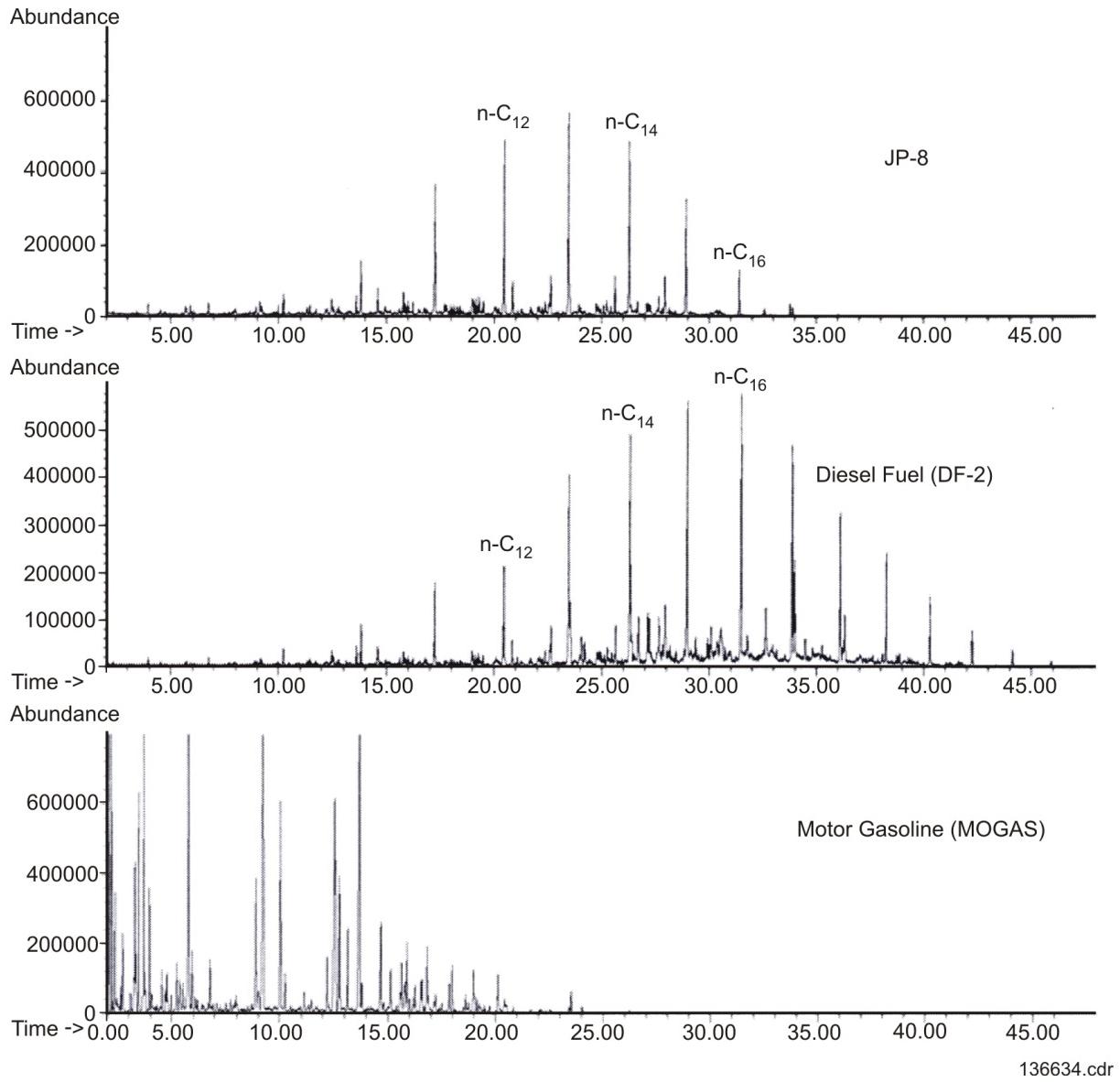


Figure 4-17. Gas Chromatograms of JP-8, Diesel Fuel, and Motor Gasoline

4.4.3 Weathered Fuels

In many field situations (e.g., fuel spills, aircraft malfunctions, and groundwater contamination), fuel samples are not pristine and may be received as weathered (in a degraded state). Weathered samples often lose their more volatile components through evaporation, altering the relative contribution of the various fuel components. Thus, proper identification of fuel type becomes more difficult. For example, the chromatogram of JP-4 in a weathered state (**Figure 4-18**) is very similar to that of JP-8 (Jet A/A-1) (**Figure 4-18**) and JP-5 (**Figure 4-16**).

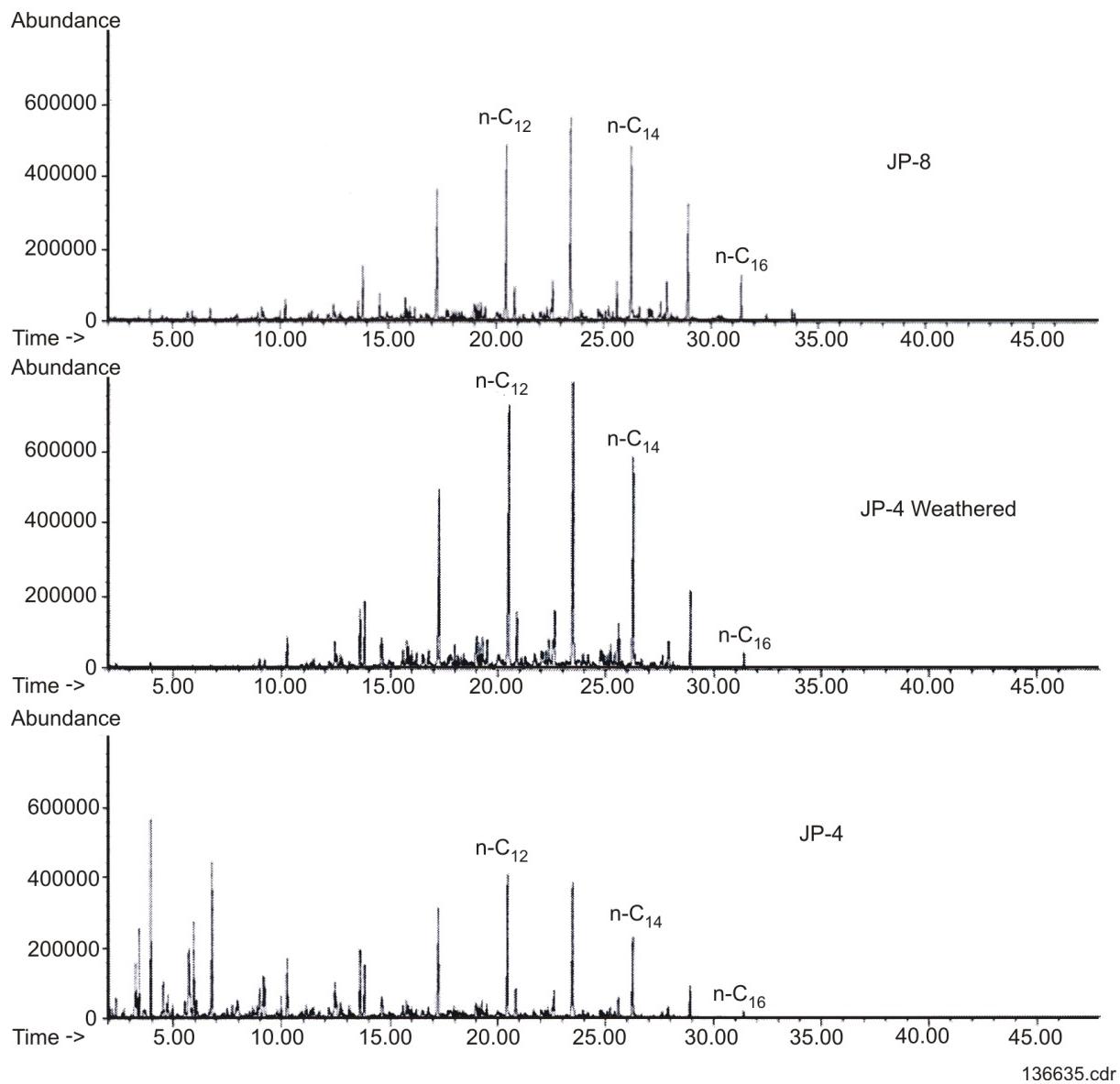


Figure 4-18. Comparison of Gas Chromatograms of Weathered JP-4, JP-8, and JP-4.

4.4.4 Mass Distribution

The percent amount of straight chain hydrocarbons can be estimated from the peaks of the fuel chromatograms. The results are shown in **Table 4-1**. The values are determined by dividing the chromatographic peak area of each of the components by the chromatographic area of the entire sample chromatogram. These results are representative of the particular fuel tested and the distribution may vary for fuels from different manufacturers and petroleum feed stocks. Because they are based on just one sample of fuel, these calculations are not average values.

Table 4-1. Area Distributions Representing Percent of Straight Chain Hydrocarbons in Fuel Samples

	Jet A	Jet A-1	JP-7	JP-5	JP-4	RG-1	RP-1	JPTS
C8	0.23	0.44	0.75	ND ¹	5.79	ND*	ND*	ND*
C9	0.78	2.35	8.63	1.29	6.64	ND*	ND*	5.46
C10	2.93	3.63	8.05	4.45	5.57	0.00	0.17	10.90
C11	4.17	3.73	9.71	10.50	3.80	0.90	1.36	13.80
C12	3.54	3.05	3.34	10.40	2.26	0.71	3.14	10.90
C13	2.79	2.50	0.31	8.14	1.49	1.10	3.05	3.99
C14	2.00	1.80	ND*	4.96	0.69	0.56	1.46	0.47
C15	1.23	0.93	ND*	0.93	ND*	ND*	0.24	ND*
C16	0.49	0.29	ND*	ND*	ND*	ND*	ND*	ND*
C17	ND*	ND*	ND*	ND*	ND*	ND*	ND*	ND*
C18	ND*	ND*	ND*	ND*	ND*	ND*	ND*	ND*
C19	ND*	ND*	ND*	ND*	ND*	ND*	ND*	ND*
C20	ND*	ND*	ND*	ND*	ND*	ND*	ND*	ND*
Total	18.2	18.7	30.8	40.7	26.2	3.27	9.42	45.5

¹ ND indicates compound not detected.

4.5 ACKNOWLEDGEMENT

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